
From: Steven Koonin <steven.koonin@gmail.com>

Sent: Tuesday, April 22, 2025 11:05 PM

To: 'Ross McKittrick' <ross.mckittrick@gmail.com>; 'Travis Fisher' <travis.scott.fisher@gmail.com>; 'John Christy' <climateman60@gmail.com>; 'Roy W. Spencer' <roywspencer@hotmail.com>; 'Judith Curry' <curry.judith@gmail.com>

Subject: RE: Apr 20 update

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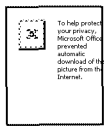
Steve: can you draft 1 & 3?

Judy: hoping you can do 8, 10 and 14 (I have info on 14 as well.)

John I think you have something on 15.

Cheers,

Ross



Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
<http://www.cfanclimate.net>

From: judith curry <curry.judith@gmail.com>
Sent: Wednesday, April 23, 2025 3:20 PM
To: Ross McKitrick
Cc: John Christy; Roy Spencer; Steve Koonin; Travis Fisher
Subject: Re: Apr 20 update

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Again, I'm open to suggestions. Maybe such issues are not necessary to mention if even the putative human forcings lead to non-damaging impacts (?)

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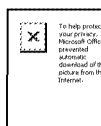
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To: judith curry
Cc: John Christy; Roy Spencer; Steve Koonin; Travis Fisher
Subject: Re: Apr 20 update

Good point about clouds. There has been a few studies pointing to 21st century downward trends in cloud cover. I have:

Dubal and Vahrenholt <https://www.mdpi.com/2073-4433/12/10/1297>

Loeb et al. <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL093047>

Loeb et al 2204 <https://link.springer.com/article/10.1007/s10712-024-09838-8>

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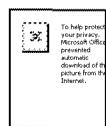
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Sent: Wednesday, April 23, 2025 4:47 PM
To: Steve Koonin
Cc: Ross McKittrick; Judith Curry; Roy Spencer; Travis Fisher
Subject: Re: Apr 20 update

I see. CO2 is about 79% of the total human forcing -(which includes aerosol cooling - a real wild card). Other GHGs are about 60% of the total forcing, so $60/79 \sim 3/4$. Together they are 139% of total forcing.

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Director, Earth System Science Center
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climateman60@gmail.com

On Apr 23, 2025, at 3:02 PM, Steven Koonin <steven.koonin@gmail.com> wrote:

You can read off the official numbers from the second IPCC figure I included. I'd do that myself, but don't have access to it at the moment.
Steven E. Koonin

On Apr 23, 2025, at 12:37, John Christy <climateman60@gmail.com> wrote:

Roy

Don't the other GHGs add about 30% to CO2 forcing (rather than 75%)?

John C.

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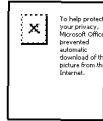
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Sent: Thursday, April 24, 2025 1:13 PM
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All

My plane was late, so I just missed the meeting with Ross, Travis and the Secretary, but did meet with Ross and Travis for over an hour immediately afterward.

Ross's summary below is what I gathered from our meeting. My sense was that the difficulties being encountered are related to a lack of communication between EPA and DoE, and even the White House, aided by the general sand-in-the-gears that some career federal employees are supplying. As Ross indicates we may have two phases - a generic, "un-authored" document fairly soon and a compete "authored" document later. The purpose of these documents is still murky as the challenge to the EF may or may not use them, but the Secretary absolutely wants the products. I mentioned again that an authored document would be a real commitment because we would have to deal with answering criticism as well as dealing with personal attacks for months.

As Ross said, we should be hearing more very soon.

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On Apr 23, 2025, at 7:49 AM, Ross McKittrick <ross.mckitrick@gmail.com> wrote:

Thanks Steve and Roy. I have a few wording suggestions but am off to a meeting so I'll write later.

Travis and I had a meeting with Secretary Wright yesterday. I'll let Travis provide a more complete summary but my takeaway was:

- Chris was unaware of the problems we had encountered until we briefed him
- The current deadline and lack of direction conflicts with his vision of the project
- He is going to try to get more time for us; and there might be an option which gives us a lot more time
- He wants us to have the time and support to produce a substantive document with our names on it. He understands why if we are held to an Apr 30 deadline we would not be able to do that.

- More to come as he digs into the situation.

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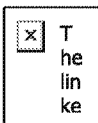
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7.1 Climate Sensitivity to CO₂ Emissions

Atmospheric CO₂ concentration has increased from its pre-industrial level of 280 parts per million (ppm) to around 412 ppm in 2021.²⁶ Human-caused warming depends not only on increasing greenhouse gases, but also on how sensitive the climate is to this increase.

Climate sensitivity is defined as the global surface warming that occurs when the concentration of CO₂ in the atmosphere is doubled, relative to pre-industrial levels.²⁷ The magnitude of the sensitivity of Earth's climate to increasing concentrations of CO₂ is at the heart of the scientific debate on anthropogenic climate change, and also the public debate on the appropriate policy response to increasing CO₂ in the atmosphere.

The magnitude of the climate sensitivity to a doubling of CO₂ concentration is associated with substantial uncertainties, which are highly consequential for policy making. If climate sensitivity to CO₂ concentration is low, then the impacts of increased emissions are expected to be relatively benign, and the benefits of emissions reductions much reduced. If the sensitivity is high, then even moderate increases of CO₂ could produce significant impacts. Climate sensitivity and estimates of its uncertainty are key inputs into the economic models that drive cost-benefit analyses and estimates of the social cost of carbon.

Since the 1979 Charney Report,²⁸ estimates in international assessment reports have put equilibrium climate sensitivity (ECS) between 1.5 and 4.5°C of warming for a doubling of CO₂ relative to pre-industrial levels. The ECS range between 1.5 and 4.5°C is characterized by the IPCC AR5 as the *likely* range (66 percent probability); the AR5 stated that ECS is *extremely unlikely* (95 percent probability) to be below 1.0°C and *very unlikely* (90 percent probability) to exceed 6°C.²⁹

This range has remained stubbornly wide, despite many individual studies claiming to narrow it. Most recently, the IPCC AR6 narrowed the *likely* range of ECS to 2.5–4.0°C and the *very likely* range to be between 2.0 and 5.0°C.³⁰ This narrowing of the range on the low end is disputed.³¹

Understanding of the uncertainties is illuminated by examining the different methods of estimating climate sensitivity and the confounding effects of feedback processes.

7.1.1 Different Ways of Estimating Sensitivity

“[W]e were under the necessity of collecting together a variety of facts, and of entering into long trains of reasoning.” (Geologist Charles Lyell)³²

Climate scientists use multiple lines of evidence to assess climate sensitivity:

- Process understanding
- Climate model simulations
- Historical observations

- Paleoclimatic observations

By itself, the equilibrium warming effect of a doubling of atmospheric CO₂ is slightly more than 1°C.³³ The large values of ECS arise from positive feedbacks that amplify the warming effect of CO₂. Water vapor feedback is positive: a warmer atmosphere may have more water vapor, which itself is a powerful greenhouse gas. Water vapor feedback is partially canceled by the fact that atmospheric temperature decreases more slowly with height above the Earth's surface when atmospheric water vapor increases. Warmer temperatures also result in less snow and sea ice cover, allowing the Earth to absorb more of the sun's radiation. Some simple estimates of these three feedbacks increase the ECS to around 2°C.³⁴

Higher values of ECS arise primarily from positive cloud feedbacks. The magnitude, and even the sign, of cloud feedbacks is the greatest source of uncertainty. Elements of cloud feedback include changes in the latitudinal distribution of clouds, changes in the distribution of cloud height (changes in low versus high clouds), changes to the phase of clouds (ice versus liquid), changes in cloud particle size (associated with changes in concentration and/or composition of aerosol particles), changes in the precipitation efficiency of clouds, and even changes in how clouds are distributed over the daily solar cycle.³⁵ It is difficult for climate models to simulate any of these cloud processes correctly owing to their small scale, let alone predict how they will change in the future. Further, cloud processes modulate the magnitudes of the water vapor, lapse rate, and the surface albedo feedbacks.³⁶

ECS can be determined from climate model simulations by doubling the concentration of CO₂, allowing several centuries for the warming to equilibrate. To avoid the necessity of long simulations, effective climate sensitivity is commonly evaluated from a 150-year simulation in response to a sudden quadrupling of CO₂. The spread of ECS values from the CMIP5 climate models (used in the AR5) was 2.0–4.7°C; the spread has increased for the CMIP6 models (used in the AR6) to between 1.8 and 5.5°C.^{37,38} Far from the science being settled in relation to the response of the climate system to increasing greenhouse gas concentrations, insofar as it is represented by climate models, uncertainties appear to be growing. The main cause of the overall upward shift in ECS in CMIP6 relative to CMIP5 is a larger positive cloud feedback, driven by changes to the cloud parameterizations in many CMIP6 models.³⁹

Climate sensitivity represents an emergent property of climate models— that is, it is not directly parameterized or tuned. However, collections of parameterizations are often chosen to produce an expected value of climate sensitivity, particularly with regards to sub-grid-scale cloud processes. Otherwise plausible models and parameter selections have been discarded because of perceived conflict with this warming rate, or aversion to a model's climate sensitivity being outside an accepted range.

The IPCC AR4 (2007) relied almost exclusively on climate models in its

assessment of ECS. The IPCC AR5 (2013) relied on both climate model determinations and determinations from the historical record, noting substantial disagreements between these two methods. The IPCC AR6 (2021) did not rely on climate model simulations in their assessment of climate sensitivity, relying on the other three methods in its assessment.

Climate sensitivity is also estimated from instrumental records of surface temperatures and ocean heat content, combined with estimates of how climate forcings (e.g., greenhouse gases, solar, volcanoes, aerosols) have changed in the past.⁴⁰ Using this information, an energy budget method is used to deduce the ECS. The greatest source of uncertainty in the energy budget method using historical data is uncertainty in the amount and composition of aerosol particles and their interactions with cloud radiative properties (the so-called aerosol indirect effect). Assumptions are also needed about ocean heat storage.

Paleoclimate proxies are used to evaluate the sensitivity of past climates, by comparing paleoclimate changes in the Earth's temperatures to estimates of changes in forcings. The two most informative periods are the last glacial maximum (around 20,000 years ago), which was about 3–7°C colder than today, and a mid-Pliocene period (roughly three million years ago), which was 1–3°C warmer than today.⁴¹ The limits on cooling during the last glacial maximum give the best single evidence that high values of climate sensitivity are unlikely. However, paleoclimate estimates are associated with very large uncertainties in the estimated temperatures and forcings. Further, estimates of climate sensitivity based on past climate states may not be representative of the current state of the climate system.

Based on a recent review article by Sherwood et al., the IPCC AR6 integrated all of the different streams of inputs using a Bayesian analysis method.⁴² The IPCC AR6 narrowed the likely range of ECS to 2.5–4.0°C.⁴³ Subsequent to publication of the AR6, independent climate scientist Nic Lewis (see also Section 2.4.1) published in the journal *Climate Dynamics* an extensive critique of the methodology used in the Sherwood et al. paper to determine the ECS.⁴⁴ Key concerns raised by Lewis include errors, outdated input values, and objective versus subjective Bayesian priors in the analysis. Lewis' analysis found that climate sensitivity is estimated to be much lower and better constrained than in the Sherwood et al. analysis – median 2.16°C (1.75–2.7°C in the 17–83 percent *likely* range), and 1.55–3.2°C in the 5–95 percent *very likely* range. This analysis implies that climate sensitivity is considerably more likely to be below 2°C than above 2.5°C.⁴⁵

7.12 Transient Climate Response

The Transient Climate Response (TCR) is of greater utility in providing an observational constraint on climate sensitivity. TCR is the amount of warming that would occur at the time when CO₂ doubles, having increased gradually by 1 percent each year over a period of 70 years. Relative to the ECS, observationally-determined values of TCR avoid the problems of uncertainties in ocean heat

uptake and the fuzzy boundary in defining equilibrium arising from a range of timescales for the longer-term feedback processes (e.g., ice sheets). TCR is more generally related to peak warming and better constrained by historical warming, than ECS. The IPCC AR6 judged the *very likely* range of TCR to be 1.2–2.4°C.⁴⁷ In contrast to ECS, the upper bound of the TCR is more tightly constrained.

A related but more flexible parameter is the Transient Response to cumulative carbon Emissions, or TCRE, which relates global temperature change to the cumulative emissions. TCRE is based upon a linear relationship between global average temperature and cumulative emissions, which holds for cumulative emissions of up to 2 teratons of carbon. For a given value of TCRE, we can calculate the amount of warming expected over a future period in response to scenarios of cumulative carbon emission. The IPCC AR6 provides a *very likely* range for TCRE of 1.0–2.3°C, with a median value of 1.6°C.⁴⁸

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Sent: Tuesday, April 22, 2025 11:05 PM

To: 'Ross McKittrick' <ross.mckittrick@gmail.com>; 'Travis Fisher' <travis.scott.fisher@gmail.com>; 'John Christy' <climateman60@gmail.com>; 'Roy W. Spencer' <roywspencer@hotmail.com>; 'Judith Curry' <curry.judith@gmail.com>

Subject: RE: Apr 20 update

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Subject: Apr 20 update

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- 10 Mortality risk from extreme heat and cold

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12 Climate change and global greening

13 Climate change and economic growth

14 Estimates of the Social Cost of Carbon

15 US vehicle-based CO2 emissions and the global climate

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Judy: hoping you can do 8, 10 and 14 (I have info on 14 as well.)

John I think you have something on 15.

Cheers,
Ross



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Empirical methods [RM]

Equilibrium Climate Sensitivity (ECS) is defined as the expected amount of warming averaged over the Earth's surface in response to a doubling of CO₂, after all climate systems have had time to adjust. Some systems, like temperatures in the troposphere, adjust very rapidly. Others may take decades or even centuries, such as the deep ocean and the cryosphere. A related metric which is sometimes more helpful on shorter time scales is the Transient Climate Response (TCR) defined as the amount of warming after 70 years in which atmospheric CO₂ goes up by one percent annually.

In large-scale General Circulation Models (aka climate models) ECS is not imposed as a direct parameter, instead it emerges from the behaviour of the underlying components of the model. These, however, are under the control of the modeler, so ultimately a model's ECS can be said to be built into it. Direct warming from CO₂ doubling is only about 1°C; the rest (to the extent more happens) arises due to climate feedbacks which are inherently more difficult to predict and model.

In 1979 the Charney (1979) Report for the US National Academy of Sciences proposed that the most likely value for ECS was 3.0°C plus or minus 1.5°C. Hence the best estimate was a likely tripling of the CO₂ effect through feedbacks. With only minor variations this range was adopted and reaffirmed by the IPCC until the most recent AR6. The range has been obtained primarily by examining the behaviour of climate models, but since key components of models are under the control of modelers this is not determinative of the actual climate's sensitivity. For example, Mauritsen and Roeckner (2020) confess regarding their Max Planck Institute model, "We have documented how we tuned the MPI-ESM1.2 global climate model to match the instrumental record of warming; an endeavor which has clearly been successful. Due to the historical order of events, the choice was to do this practically by *targeting an ECS of about 3 K using cloud feedbacks*, [emphasis added] as opposed to tuning the aerosol forcing." In other words, without appealing to fundamental physics the modelers chose an ECS of 3 K then tuned the cloud feedbacks to match their intended result.

A significant amount of effort has gone into estimating ECS empirically. There are several challenges to this work.

- First, it requires good data but observations of some key climatic systems, especially the oceans, are available in only very limited amounts.
- Second, identifying the effect of CO₂ requires simultaneously identifying the effect of aerosols. Climate models exhibit warming in response to GHGs but cooling in response to aerosols (Schwartz et al. 2007). Observed 20th century warming can be shown to be consistent either with low ECS and low aerosol cooling or high ECS and high aerosol cooling. Since fossil fuel use adds both GHGs and aerosols to the atmosphere, both effects need to be estimated to isolate the warming effect of CO₂. Over time the IPCC's estimate of the cooling effect of aerosols has declined (Lewis 2022).
- Third, the simple empirical model typically used for the estimation, called an Energy Balance Model, requires estimating a feedback parameter which appears in the denominator of the equation for ECS. A small amount of uncertainty about the number in the denominator of a fraction can lead to very large uncertainties in the magnitude of the fraction itself. Roe and Baker (2007) pointed out that uncertainties in climate feedbacks are "highly amplified" in the resulting ECS.

Since 2012 many studies have appeared in the literature tackling these various uncertainties. A recurring theme is that ECS estimates based on historical data turn out to be smaller than ECS estimates inferred from climate models (Sherwood and Forest 2024). An early estimate (Stern and Kaufmann 2000) was 1.6°C, though this predated development of the Energy Balance Model method. Figure 1.6.1 shows the point or best estimates from 17 subsequent studies all appearing in the peer-reviewed literature after the TSD. The Charney range is shown for contrast. The average ECS estimate in the post-2012 sample is 1.8°C. The highest estimate, from Sherwood et al. 2020, is shown in red: it is the one that was used by the IPCC for the AR6 (Forster et al. 2021). The one adjacent to it, Lewis (2022), shows the result of, among other things, using the same method but applying more updated aerosol forcing data in the AR6 as well as some other recent updates to the source data. These updates dropped the ECS best estimate back down closer to the usual empirical range. The IPCC, following Sherwood et al. (2020) had estimated only a 5 percent probability that ECS was below 2.3°C was only 5 percent, whereas Lewis (2022) estimated it was over 50 percent.

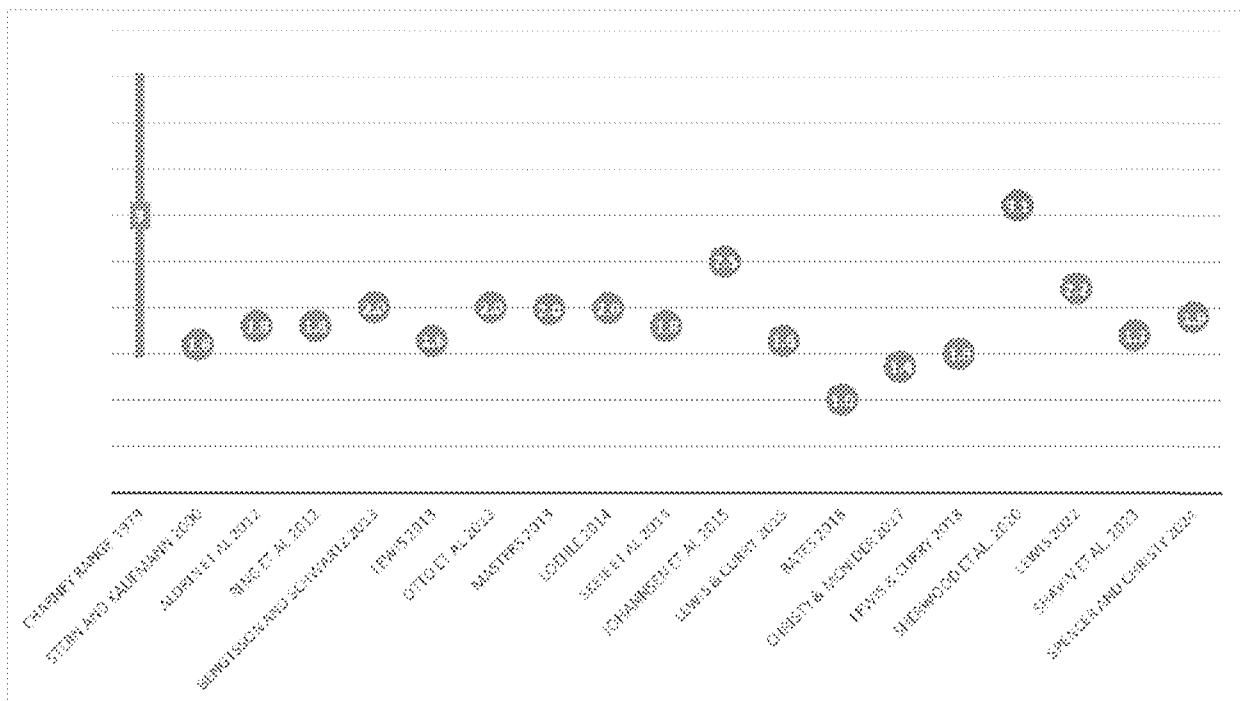


Figure 1.6.1: Empirical best estimates of ECS

A recent argument, one which the IPCC emphasized, that empirical ECS estimates might understate the future warming response to GHGs is based on a so-called “pattern effect” (Forster et al 2021). The tropical Pacific is believed to be highly influential on the overall efficiency with which the Earth’s climate radiates heat to space, but heat in some parts is more efficiently removed than from others. If in a warming climate there is a weakening of the west-to-east temperature gradient in the tropical Pacific the result would be a concentration of warming in a region where heat is less efficiently removed, raising the ECS of the Earth’s climate system. Most climate models simulate that rising GHGs will weaken the east-west temperature gradient, which led the IPCC in the AR6 to conclude that empirical ECS estimates understated what would be the *future* observed ECS value.

However Seager et al. (2019) pointed out that, contrary to models, the east-west temperature gradient has been strengthening rather than weakening over time. They further argued that the mechanism predicting otherwise in climate models was based on a faulty characterization of oceanic dynamics and there is no reason to expect the gradient to weaken. A similar argument was recently made by Lee et al. (2024), who concluded that “the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere”, in other words GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. This implies, if anything, that future ECS in a warming climate will be lower than at present.

In summary, while the ECS range in climate models is very wide, historically climate models have embedded processes and assumptions that about secondary feedbacks that approximately triple the warming from CO₂. Empirical estimates since the TSD however imply the climate is much less sensitive to CO₂ than this, with the estimates centered at or below 2°C. As discussed in Section 1.4.2 this is supported by studies which show climate models on average estimate too much warming at the surface and in the troposphere compared to observations over the past 50 years, and low-ECS models do better than high-ECS ones. Also this aligns with evidence from consistent fingerprinting (Section 1.5.1) that model responses to GHGs need to be scaled down quite a bit to align with observed trends. As will be discussed in Section 3.6, ECS values in the range of 2.0°C imply very low Social Cost of Carbon values.

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Subject: Re: Apr 20 update
Attachments: Chapter 0 &1 [SEK Apr 22]-RS-edits.docx

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0. Introduction

This document provides technical support for the endangerment and cause or contribute analyses concerning greenhouse gas (GHG) emissions under section 202(a) of the Clean Air Act. It does not convey any judgment or conclusion regarding the question of whether GHGs may be reasonably anticipated to endanger public health or welfare, as this decision is ultimately left to the judgment of the Administrator.

Assessing the dangers created by GHG emissions from US road vehicles involves a long chain of inference.

1. How will emission of GHGs (principally CO₂) influence the future climate?
2. How will the climate change under those growing influences?
3. How will those changes affect ecosystems and society?

The current certainties and uncertainties in each of these questions are considered in the following three chapters. The presentation is based on official UN and US government assessment reports, the peer reviewed literature and, in some cases, straightforward analyses of official data. However, the usual attribution of climate change to anthropogenic influences involves uncertainties regarding natural sources of climate change, which remain poorly understood. So, while most the following treatment emphasizes the currently popular paradigm of climate change as being due to changes in the global energy balance between absorbed sunlight and emitted heat radiation at the top of the atmosphere, climate can also change from unforced, chaotic variations within the climate system itself, such as atmospheric circulation-induced changes in cloud cover or changes in the rate of overturning of the global oceans. This “known unknown” should be kept in mind in discussions of anthropogenic climate change.

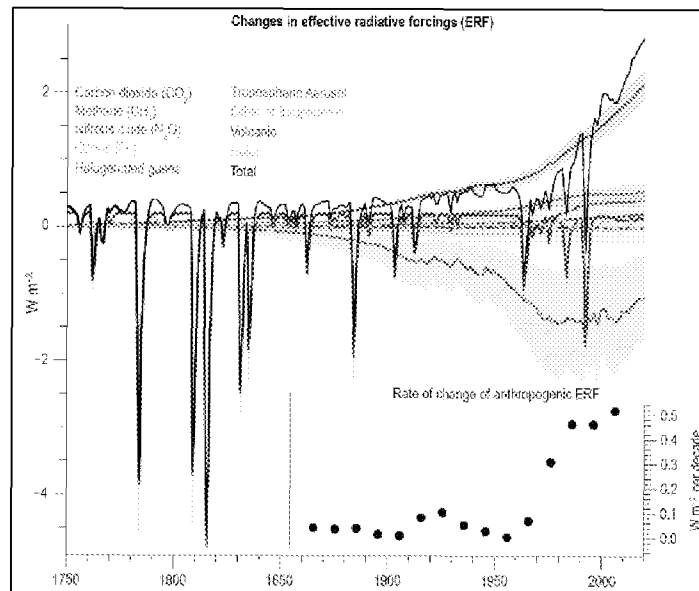
1. Human influences on the climate

1.1. Radiative forcing

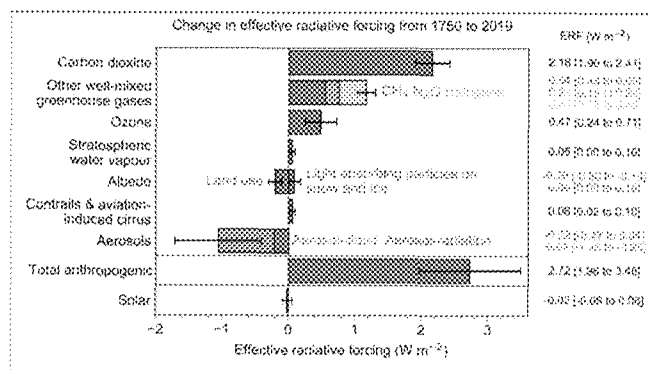
The earth is warmed by the sunlight it absorbs and cooled by the radiative heat it emits to outer space. Averaged over Earth, each of these processes involve power flows of about 240 W/m². When they are in balance, the earth neither warms nor cools and the global temperature is constant. Human (and some natural) influences on the climate alter this balance and so cause the climate to change.

Influences on the climate are quantified by “radiative forcing”, the extent to which they disturb the warming/cooling balance; a positive forcing warms while a negative forcing cools.

The history of total estimated radiative forcing since 1750 and its present-day components are shown in the following two figures from IPCC AR6:



<https://www.ipcc.ch/report/ar6/wg1/figures/chapter-2/figure-2-10/>



<https://www.ipcc.ch/report/ar6/wg1/figures/chapter-7/figure-7-6/>

These graphs show that the total radiative forcing is comprised of natural and anthropogenic components. The natural component is largely volcanic aerosols, which exert an episodic cooling effect; solar variations are deemed negligible. The anthropogenic component was negligible before about 1900 and has increased steadily since, rising to almost $3 W/m^2$ today. However, this is still only about 1 percent of the unperturbed radiation flows, making it a challenge to isolate the effects of anthropogenic forcing since state-of-the-art satellite estimates of global radiative energy flows are only accurate to a few Watts per sq. meter. Natural sources of global energy imbalance other than volcanoes are not included in these graphs because they remain largely unknown.

Carbon dioxide is the largest human influence on the climate and the one most relevant to the effects of motor vehicles; its emissions are accumulating in the atmosphere, as described in the following section. It exerts a warming influence by decreasing the cooling power of the

atmosphere. Other greenhouse gases (methane, nitrous oxide, halogens, and ozone), which act similarly, currently add another 75% to CO₂'s warming. Aerosols exert a cooling effect, although with large uncertainties in the way they catalyze the formation of reflective clouds. As a result, understanding of the causes of recent warming is not just through the warming effects of CO₂, but also the more uncertain cooling effects of sulfate aerosols.

1.2. Future radiative forcing

Carbon dioxide's warming influence depends upon how much "extra" CO₂ accumulates in the atmosphere- i.e., it's concentration. The CO₂ level as recorded at the Mauna Loa observatory in Hawaii is generally used as the representative global average concentration. The data are available online at <https://gml.noaa.gov/ccgg/trends/index.html>. The concentration was about 316 ppm at the start of the record in 1959 and is now about 425 ppm, a 34 percent increase.

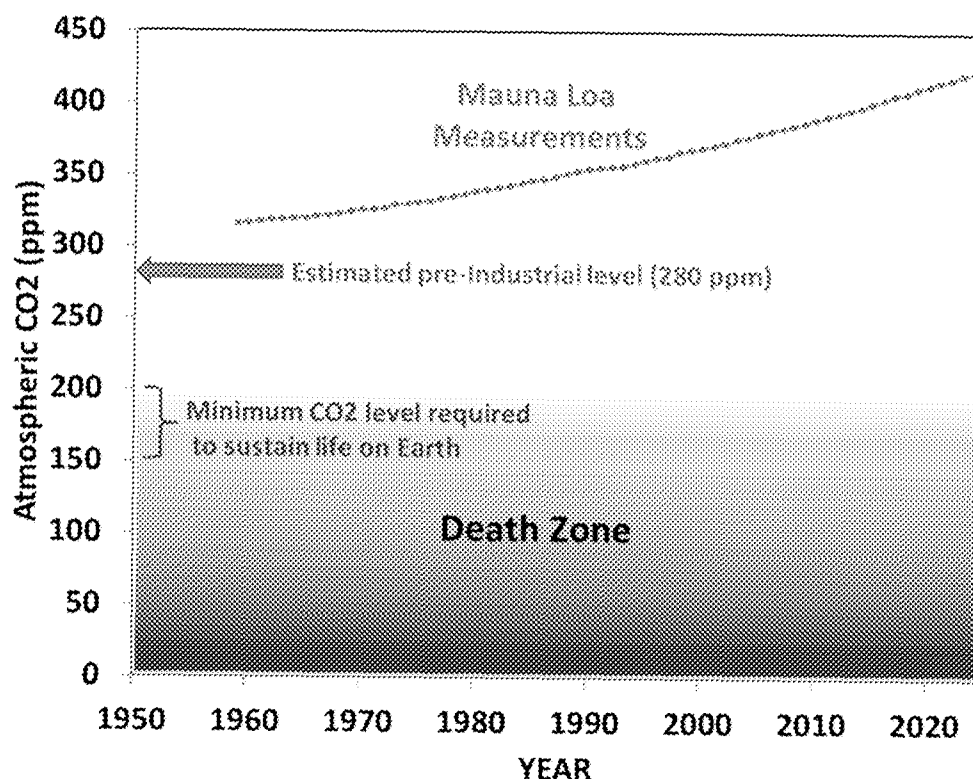


Fig. X. Yearly average atmospheric CO₂ concentrations (1959-2024) measured at Mauna Loa, HI (green) compared to the estimated pre-Industrial CO₂ concentration of 280 ppm, and the estimated minimum levels required to sustain life on Earth (150 to 200 ppm).

The annual increase in concentration is only about half of the CO₂ emitted because land and ocean processes absorb "excess" CO₂ at a rate approximately 50% of human emissions. Thus,

future concentrations, and hence future human influences on the climate, depend upon two components: (1) future rates of global human CO₂ emissions, and (2) how fast the land and ocean remove extra CO₂ from the atmosphere. We discuss each of these in turn.

1.2.1. Emissions scenarios

Assessing the future dangers of GHG emissions requires assumptions about what those emissions will be. Future emissions, and hence human influences on the climate, will depend upon future demographics, economic progress, regulation, and the energy and agricultural technologies in use. Various assumptions about each of those lead to projections of greenhouse gas emissions and concentrations, aerosol concentrations, and changes in land use, which ultimately can be combined into assumptions about anthropogenic radiative forcing.

Because of the great uncertainties about the decades to come, instead of making precise predictions of future concentrations, the IPCC created a set of scenarios meant to span a plausible range of possibilities for population, economy, technology, and so on. Scenarios are labeled by a number indicating the anthropogenic radiative forcing expected in 2100 under that scenario. Thus, a scenario labeled with a “6” corresponds to 6 W/m² of human-induced radiative forcing (warming) at the end of the century. (Recall current anthropogenic radiative forcing is about 2.7 W/m².) Unfortunately, IPCC Emission scenarios have long been biased toward excessive warming.

For the IPCC 3rd and Fourth Assessment Reports a set of emission projections from the *Special Report on Emission Scenarios* were used, and hence were referred to as the SREP scenarios. McKittrick et al. (2012) showed that, when converted to per capita terms, the SREP scenario distribution was skewed upwards and incompatible with observed trends. McKittrick and Wood (2013) further showed that global energy market dynamics constrained global per capita CO₂ emissions to an extent not reflected in IPCC scenarios. The bias of the SRES scenarios was confirmed by analysis in Hausfather et al. (2019) who showed that observed atmospheric CO₂ levels tracked the lowest of the SRES forecast range.

For the Fifth Assessment Report the IPCC developed a new set of scenarios called the Representative Concentration Pathways (RCP). Each RCP is identified by a number representing the increase in warming forcing in Watts per square meter over the 21st century resulting from GHG emissions. The RCP scenarios are thus called RCP2.6, RCP4.5, RCP6.0 and RCP8.5. RCP2.6 (implying a gain of 2.6 Watts per square meter) projects a GHG concentration pathway which implies warming remains well below 2°C. At the other end of the scale RCP8.5 is an extreme outcome implying nearly 5°C warming just in this century.

In both the academic literature and popular media RCP8.5 came to be referred to as the no-policy baseline, or “business-as-usual” scenario. It was used in this way to generate the reference outcome supposedly representing the 21st century world in the absence of

emission reduction policies. But RCP8.5 was in fact an extreme high emissions scenario and its usage as a baseline has been grossly misleading. Hausfather and Peters (2020) writing in a commentary in *Nature* magazine, pointed out that RCP8.5 was developed as an extreme worst-case scenario, and its misuse as a “business as usual” baseline has resulted in a large number of misleading studies and media reporting:

RCP8.5 was intended to explore an unlikely high-risk future. But it has been widely used by some experts, policymakers and the media as something else entirely: as a likely ‘business as usual’ outcome. A sizeable portion of the literature on climate impacts refers to RCP8.5 as business as usual, implying that it is probable in the absence of stringent climate mitigation. The media then often amplifies this message, sometimes without communicating the nuances. This results in further confusion regarding probable emissions outcomes, because many climate researchers are not familiar with the details of these scenarios in the energy-modelling literature.

(Hausfather and Peters 2020)

The implausibility of the RCP8.5 scenario was examined by Burgess et al. (2021). They noted that RCP8.5 has already diverged from observed energy use trends, and the near future trends diverge sharply from those of the International Energy Agency (IEA) which provides market-based projections of energy use for coming decades. IEA trends are based on plausible extrapolations of current economic and demographic trends, and the results run below the entire envelope of RCP projections, implying not only that RCP8.5 is dubious, but even lower emission scenarios are looking unlikely. Burgess et al. comment (p. 8):

Beyond 2040, if the trends anticipated by energy agency forecasts continue, carbon intensity will continue diverging from AR5 and SSP baselines—especially from higher-emission scenarios such as RCP8.5, due to the assumptions about fossil-fuel expansion in these scenarios that are increasingly implausible.

The problem of bias towards alarmism in the climate impacts literature fueled by implausible extreme high emission scenarios was confirmed in a literature analysis by Pielke Jr. and Ritchie (2020). They found (p. 32) that between 2010 and 2020 some 16,800 scientific papers had been published using the RCP8.5 scenario, and (p. 16) that about 4,500 of the articles linked RCP8.5 with the concept of “business-as-usual”. They provided analyses of how RCP8.5 was misused not only by individual researchers, but by influential science agencies like the IPCC and the US National Climate Assessment (USNCA), which has directly led to misleading coverage in prominent media outlets. They provide the following example (p. 30):

The USNCA employed RCP8.5 as a baseline scenario, despite warning against such use, and compared it to RCP4.5 throughout its report to generate quantitative economic

estimates of the benefits of mitigation. In a front-page story, the *New York Times* promoted the report's misuse of RCP8.5 as a baseline scenario:

"A major scientific report issued by 13 federal agencies on Friday presents the starkest warnings to date of the consequences of climate change for the United States, predicting that if significant steps are not taken to rein in global warming, the damage will knock as much as 10 percent off the size of the American economy by century's end."

Pielke and Ritchie (2020) reported new studies using RCP8.5 were appearing in the literature at a rate of about 20 per day, with about two per day specifically linking RCP8.5 and "business as usual." They conclude (p. 34) that the climate research community has spent a decade "committing scientific resources to science fiction" (emphasis added):

"Derived estimates from RCP8.5 as "business as usual" such as future climate impacts, the impacts avoided from mitigation and the cost effectiveness and benefits of mitigation have no real-world meaning... **The scientific literature has become imbalanced in an apocalyptic direction.**

(Pielke Jr. and Ritchie p. 34)

The IPCC later modified the RCP scenarios to the "Shared Socioeconomic Pathway" or SSP scenarios, but these have continued the pattern of bias shown with the RCP and SRES scenarios. Figure 1.4.3.2, generated using the Resources for the Future Global Energy Outlook tool (RFF 2025). The black line shows total global observed CO₂ emissions from the International Energy Agency (IEA). The solid green line is the emission trajectory developed by BP energy taking account of current emission control policies and global energy use outlooks. current policy proposals. It overlaps a solid black line which represents the emission projection from the IEA also taking account of energy use projections and current policies. The dashed lines show the range of IPCC SSP policies.

Carbon dioxide emissions (Million metric tons), by Outlooks & Scenarios. Filtered by Region: World; Fuel: All; Outlook: 2023 Shell (Sky 2050).

Source: RFF Global Energy Outlook at www.rff.org/geo

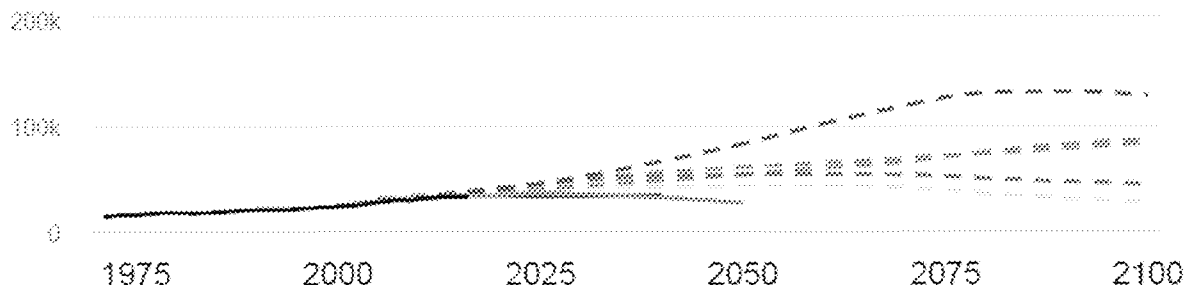
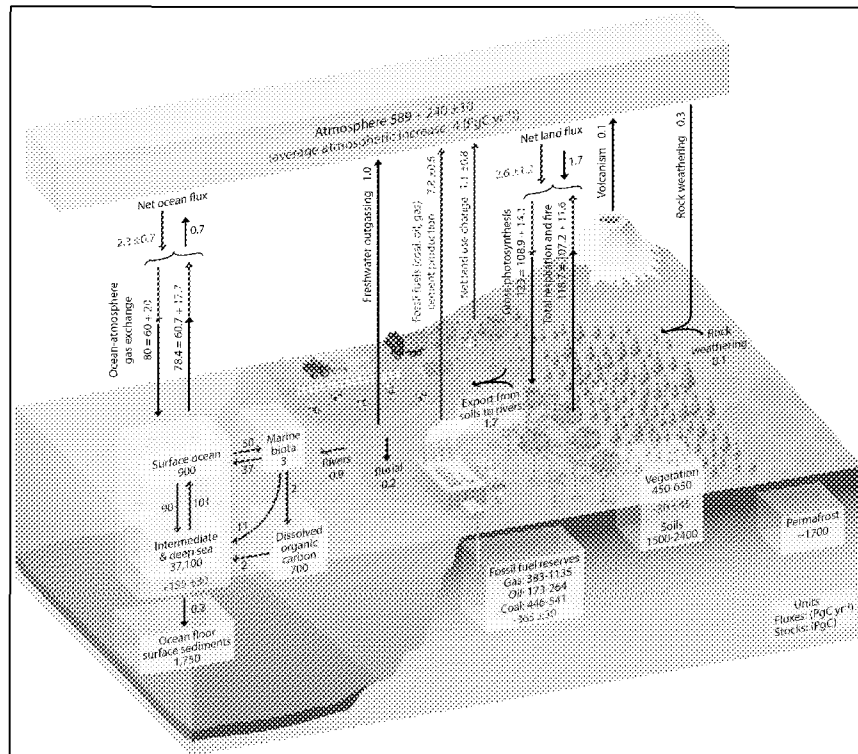


Figure 1.4.3.2. Observed and projected CO₂ emissions. Source: RFF (2025).

As of 2023 global CO₂ emissions have been tracking *well below* the SSP scenarios especially the two highest ones (SSP5-8.5 and SSP3-7.0). As mentioned, most of the climate model projections relied upon for energy policy decisions have been from these two emissions scenarios or their RCP analogues, which exaggerated and unrealistic (e.g. Ritchie and Dowlatabadi, 2017; Pielke & Ritchie, 2017; Pielke & Ritchie, 2021).

1.2.2. The carbon cycle relating emissions and concentrations



Global carbon cycle models relate concentrations to emissions using estimates of various land and ocean processes that remove CO₂ from, and emit CO₂ into, the atmosphere. Our understanding of these processes was reviewed by Crisp et al. (2021). The natural fluxes of CO₂ in and out of the Earth's surface are very large, many times anthropogenic emissions, but those CO₂ sources and sinks were assumed to be in approximate balance in pre-Industrial times, as evidenced by relatively constant levels of atmospheric CO₂ in centuries past derived from air bubbles in ice cores. This is one of several reasons why increasing atmospheric CO₂ levels are believed to be dominated by anthropogenic sources.

Specifically, fossil fuel burning (and to a lesser extent land use [biomass burning] and cement production) has led to steadily increasing CO₂ levels in the atmosphere, as shown in Fig.X

CO₂ emissions from fossil fuel burning is a small fraction of the natural carbon cycle components. About 44,000 Gigatonnes of carbon-equivalent (GtC) are stored in the atmosphere and oceans, mostly in the form of CO₂. (Ciais et al. 2013). Between 150 and 200 GtC are released naturally each year through oceanic outgassing and land-based processes like plant decay and animal respiration. A variable but roughly equivalent amount is absorbed each year by the land and oceans, with a small net loss from the atmosphere because the formation of deep ocean sediment sequesters some carbon permanently. Global fossil fuel consumption and cement manufacture released about 10.3 GtC in 2023, up from 6.2 GtC in 1990 (Ritchie et al. 2024). Of this, about half is naturally sequestered through plant

growth and oceanic uptake while the remainder, about half, adds to the atmospheric stock (Ciais et al. 2013).

As noted, each year natural processes remove a net amount of CO₂ equivalent to about 50% of global emissions. Thus, anthropogenic CO₂ emissions average twice what is required to explain the atmospheric rise in CO₂ concentration. The near-constancy of that 50% fraction (the “airborne fraction”) also means that the more CO₂ humanity produces, the faster Nature removes it from the atmosphere. That 50% fraction changes somewhat from year to year due to natural carbon cycle imbalances from El Nino, La Nina, and varying weather patterns. There was also a substantial additional reduction in atmospheric CO₂ after the 1991 eruption of Mt. Pinatubo, a curious result that has yet to be explained (Angert et al., 2004).

The main processes which remove excess CO₂ from the atmosphere are increased production of land vegetation (especially at high latitudes), some increase in the sequestering of carbon in soils, and uptake of CO₂ by the ocean due to the increasing partial pressure of atmospheric CO₂ over that of CO₂ dissolved in the ocean. All twenty land carbon cycle models tracked by the Global Carbon Project (Friedlingstein et al., 2024) show land processes have been removing excess CO₂ at an increasing rate since 1959. This is consistent with a “global greening” phenomenon observed by satellites since monitoring of global greenness began in the 1982. This greening has been traced to CO₂ fertilization and greater drought tolerance of plants exposed to elevated CO₂ levels. While there had been some uncertainty whether a greening trend continued beyond 2000, the most recent research (Chen et al., 2023) has shown continued greening, with even some slight acceleration since 2000. Global greening is discussed further in Section 3.1.

While land vegetation has been responding positively to more atmospheric CO₂, uptake of extra CO₂ by ocean biological processes remains too uncertain to be reliably measured. Our current understanding of these and many more carbon cycle processes was reviewed by Crisp et al. (2021).

1.3. CO₂ as a “pollutant”

Whether CO₂ falls in the legal category of pollutant is ultimately a legal question. But the answer should be informed by the scientific similarities and differences between CO₂ and other generally acknowledged pollutants.

CO₂ is fundamentally different from criterion air contaminants like SO₂ and NO_x for two reasons. First, the damage from criterion air contaminants stems from their local ground-level concentration, since that is what affects human welfare. But local variations in CO₂ levels do not affect human health, the potential channel of influence is through variations in the global climate which operates through the global average atmospheric CO₂ concentration.

(Another influence is the positive local effect on crop productivity which will be discussed in Section 3.2).

The second reason is that policy can only change the rate of emissions, not the concentration in the atmosphere. For criterion air contaminants the rate and concentration are closely connected because the lifetime is short and the concentration is small. When emissions are reduced the local pollution concentration drops rapidly, usually on a time scale of a few days. Not so with the global average CO₂ concentration since global carbon cycle is vast and slow. A change in local emissions today will only have a very small global effect, and only after a long time lag. After a pulse (release) of CO₂ emissions to the atmosphere only about 40 percent ($\pm 15\%$) of the extra CO₂ will have been sequestered after twenty years. After a thousand years about 75 percent ($\pm 10\%$) will have been sequestered, and the remainder will gradually be removed over the ensuing tens of thousands of years (Ciais et al. 2013, pp. 472-473). Consequently US CO₂ emission reductions will take decades or centuries to lead to a reduction in the global CO₂ concentration.

To reduce the atmospheric stock of CO₂, assuming the entire increase is anthropogenic, would require emissions to fall below the natural sequestration rate. Since that rate has been averaging about 50% of emissions, a reduction of global emissions by 50% would (at least temporarily) halt the rise in atmospheric CO₂. The 1997 Kyoto Protocol proposed to cap industrial nations' CO₂ emissions at a modest five percent below 1990 levels by the year 2012. Even though this policy ended up too costly for most nations to implement, full compliance would not have substantially reduced atmospheric CO₂ levels. They would only slightly slowed CO₂ growth, reaching their projected 2100 level in 2105 instead (Wigley 1998). Similarly, Lomborg (2016) used the widely-used MAGICC climate model and showed that full compliance with the Paris Accord would delay hitting the baseline year 2100 levels about a decade later instead.

Thus, in contrast with conventional air pollution control, local actions yield extremely small local effects, and only after a long time lag. The practice of referring to unilateral US reductions as “combatting climate change” or “taking action on climate” reflects a profound misunderstanding of the scale of the issue.

1.4. Summary

- When the two components required to estimate future atmospheric CO₂ concentrations are combined (anthropogenic emissions estimates along with carbon cycle model estimates of atmospheric CO₂ removal), we get estimates of future CO₂ concentrations and hence the radiative forcings required by climate models to estimate future rates of warming.
- For decades the IPCC has used emission scenario envelopes that are grossly exaggerated against observed trends.

- The vast majority of academic climate “impacts” studies in recent years are based on scenarios like RCP8.5 that are implausible to the point of being deceitful. Usage of the RCP8.5 scenario amplifies the putative dangers of future baseline emissions and exaggerates the associated benefits of emission reduction policies.
- Despite ample evidence that scenario envelopes are exaggerated, and despite heavy criticism of this practice in the peer-reviewed literature, the IPCC’s most recent scenario set called SSP carries on with this deceptive pattern.
- Unlike criterion air contaminants, local emissions and local levels of CO₂ have no human health implications. The only potential effects are CO₂ fertilization of plants (a benefit) and modifications of the global climate.
- The global carbon cycle heavily dampens the effect of changes in local (e.g. U.S.) CO₂ emissions. Even global-scale emission reductions will have only small effects, long in the future.

From: Judith Curry <curry.judith@gmail.com>
Sent: Friday, May 9, 2025 2:45 PM
To: Steven Koonin
Cc: Roy Spencer; John Christy; Ross McKittrick; Travis Fisher
Subject: Re: attribution chapter
Attachments: 7 Attribution.[RM].May08.docx

New attribution chapter is attached (ross sent this yesterday)

On Fri, May 9, 2025 at 11:34 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Judy – your email text says “attribution chapter” but you attached chapter 5 (climate sensitivity). Can you straighten out the confusion?

SEK

From: Judith Curry <curry.judith@gmail.com>
Sent: Friday, May 9, 2025 12:27 PM
To: Roy Spencer <roywspencer@hotmail.com>; John Christy <climateman60@gmail.com>; Steve Koonin <steven.koonin@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>
Subject: attribution chapter

Latest version of attribution chapter is attached, Ross and I have hashed through this pretty thoroughly, we look forward to your comments

--

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7 Uncertainties in Climate Change Attribution

7.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) distinguishes between detection of climate change and attribution of cause. As defined by the IPCC AR6 WGI Glossary (IPCC, 2025):

Detection: “Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%.”

Attribution: “Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of confidence.”

Both steps rely on statistical analysis. Detection focuses on whether changes are significant enough to stand out from random variation regardless of cause. Attribution involves comparison of observed events to model-generated counterfactuals. Since experimentation on the climate is not possible attribution requires statistical inference to assess how much human activities, such as GHG emissions, versus natural factors, like volcanic eruptions, explain observed changes. Attribution methods assume all external and internal drivers of the system are known and represented.

There are ongoing scientific debates around attribution methods, especially for attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement. The Fourth Assessment Report: The Physical Science Basis (Hegerl et al., 2007) explained it as follows:

‘Attribution’ of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence... unequivocal attribution would require controlled experimentation with the climate system. Since that is not possible, in practice attribution of anthropogenic climate change is understood to mean demonstration that a detected change is ‘consistent with the estimated responses to the given combination of anthropogenic and natural forcing’ and ‘not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings’ (IPCC, 2001)... The approaches used in detection and attribution research described above cannot fully account for all uncertainties, and thus ultimately expert judgement is required to give a calibrated assessment of whether a specific cause is responsible for a given climate change.

The Fifth Assessment Report Working Group II makes the following statement: (Cramer et al., 2014):

“Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high-quality, long-

term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question.”

Because of the complexity of the causal chains in the climate system, investigation of these relationships is exceptionally challenging.

7.2 Attribution methods

The Intergovernmental Panel on Climate Change (IPCC) employs several attribution methods to assess the causes of observed climate changes, distinguishing between natural and human-induced factors. Below is a concise description of the key methods that have been used by the IPCC:

Optimal Fingerprinting uses linear regression to explain variations in observed climate data as a weighted sum of climate model simulations run with and without anthropogenic forcings. The data used in the regression model are weighted to try to minimize the influence of random noise and the estimation method is chosen to take account of climate model error.

Time Series Analysis exploits statistical differences between anthropogenic forcing and natural variability to see which one dominates observed temperatures, and also uses variations in the timing of changes to determine if causal dependence across data series can be inferred.

Process-Based Attribution focuses on understanding the physical mechanisms behind observed changes. This approach combines observations, climate models, and theoretical understanding to attribute changes in specific processes to forcings. This approach is often used for regional climate phenomena, such as monsoon changes or polar amplification

Extreme Event Attribution assesses in the role of human influence in the likelihood of occurrence or intensity of extreme weather events (e.g. heat waves, droughts). Methods include:

- Probabilistic Event Attribution uses large ensembles of climate model simulations to compare observed events to model-generated counterfactuals
- Storyline Approach examines the physical processes driving an event and evaluates how anthropogenic forcings may have modified those processes

7.3 Attribution of global warming

Attribution statements for global warming in the three most recent IPCC Assessment reports are:

AR4: “Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations.” (IPCC, 2007)

AR5: “It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. The best estimate of the human- induced contribution to warming is similar to the observed warming over this period.” (IPCC, 2013)

AR6: “The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver of tropospheric warming since 1979.” (IPCC, 2021)

The AR4 and AR5 attribution statements reference the warming since the mid-20th century, the period when greenhouse gas emissions began rapidly increasing. The words “most” and “more than half” are deliberately imprecise, potentially ranging from 51 to 99% of the warming – presumably this imprecision is to account for structural uncertainties such as natural internal variability. The confidence level increases from *very likely* to *extremely likely* from AR4 to AR5. The structure of the attribution statement in the AR6 is fundamentally different, referencing the warming to the period 1850-1900. The AR6 attribution statement is more precise numerically, but with a lower level of confidence at “likely” – the AR6 attributes essentially all of the warming to increases in greenhouse gases. The most confident statement from the AR6 relates to the tropospheric warming since 1979, using the words “main driver” and “*very likely*.”

There are three areas of substantive criticism of the IPCC assessment of the causes of the recent warming: inadequate assessment of natural climate variability, inappropriate statistical methods, and substantial discrepancies between models and observations. The latter is discussed in Chapter 7. The other two factors are discussed herein. Both of these issues are relevant not only in context of the main policy-relevant statement of the IPCC concerning attribution of the recent warming, but also because the global warming attribution provides the basis for extreme event attribution

7.3.1 Natural climate variability

The IPCC AR6 states that natural external drivers since 1850-1900 have changed global surface temperature by –0.1°C to +0.1°C, and internal variability has changed it by –0.2°C to +0.2°C – on average, having essentially no net impact on the warming since 1850-1900. This assessment of the contributions of natural variability has been disputed by a number of publications that question the magnitudes of the contributions from solar forcing and internal variability from the large-scale ocean circulations (R Connolly et al., 2021; W Soon, 2023).

If the Equilibrium Climate Sensitivity to CO₂ is low (Chapter 5), then natural climate variability becomes more important in the attribution of the recent warming. Further, if natural variability is higher, then estimates of the Equilibrium Climate Sensitivity from the historical period would be lower (Scafetta, 2023).

Solar variability

The IPCC AR5 concluded that the best estimate of radiative forcing due to Total Solar Irradiance (TSI) changes for the period 1750–2011 was 0.05 W/m^2 (Myrhe et al., 2014). The IPCC AR6 acknowledges a much larger range of estimates of changes in TSI over the last several centuries, stating that the TSI between the Maunder Minimum (1645–1715) and the second half of the twentieth century increased by $0.7\text{--}2.7 \text{ W/m}^2$, a range that includes both low and high variability TSI data sets (Gulev, 2021). However, the recommended forcing dataset for the CMIP6 climate model simulations used in the AR6 for attribution studies averages two data sets with low solar variability (Matthes, 2017).

While the IPCC AR6 shows a substantially greater solar impact than does the AR5, the overall impact on the climate was assessed to be small compared to anthropogenic forcing of climate change. However, the impact of solar variations on the climate is uncertain and subject to substantial debate – something that you would not infer from the IPCC assessment reports (Lockwood, 2012; Connolly et al., 2021).

Exactly how TSI has changed over time has been a challenging problem to resolve. Since 1978, there have been direct measurements of TSI from satellites. However, the data exhibit non-negligible inconsistencies, and interpreting any multi-decadal trends in TSI requires comparisons of observations from overlapping satellites. There are several rival composite TSI datasets, disagreeing as to whether TSI increased or decreased during the period 1986–96 (the ACRIM gap; see Chapter 4). Further, the satellite record of TSI is used for calibrating proxy models, whereby past solar variations are inferred from sunspots and cosmogenic isotope measurements (Velasco Herrera et al., 2015).

There is substantial evidence for high solar activity in the second half of the 20th century (starting in 1959) and extending into the 1990's, before a decline in the early 21st century; this period is often termed the “Modern Maximum.” (Chatzistergos et al., 2023; Solanki et al., 2004; Usoskin et al., 2007). However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz, 2021).

As a result of this uncertainty, some reconstructions for past values of TSI (since 1750) have low variability, implying a very low impact of solar variations on global mean surface temperature, whereas datasets with high TSI variability can explain more than 70% percent of the temperature variability since preindustrial times (Scafetta, 2013; Stefani, 2021). Hence, the choice of which TSI satellite record used in an analysis can substantially influence how much climate change is attributed to human versus natural forcings.

There is growing evidence that other aspects of solar variability, which are referred to as solar indirect effects, amplify TSI forcing or are independent of TSI forcing. Scafetta et al. (2023) suggests that ~80% of solar influence on climate may stem from non-TSI mechanisms. Candidate processes include: solar ultraviolet changes; energetic particle precipitation; atmospheric-electric-field effect on cloud cover; cloud changes produced by solar-modulated galactic cosmic rays; large relative changes in the magnetic field; and the strength of the solar wind. Solar indirect effects are not included in climate models, although indirect methods of estimating these effects suggest

significant influence. However, claims of non-TSI mechanisms influencing climate are uncertain and debated.

Natural variability of large-scale ocean circulations

Variations in global mean surface temperature are linked to recurrent large-scale variations in ocean circulation patterns. These circulation patterns include the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO). These circulation patterns influence ocean heat uptake and heat distribution, and also influence atmospheric circulation patterns and cloud distributions. There is some debate as to whether these variations are strictly internal to the climate system, or whether this variability can have a solar/astronomical origin or can be influenced by large volcanic eruptions.

While climate models simulate the large-scale ocean circulations and internal climate variability, the simulated magnitude in the multi-decadal band is too low in most models relative to observations, and the phasing of the variability in long-term climate simulations is not synced with the actual, observed climate variations (Kravtsov et al. 2024). Averaging multiple simulations from climate models effectively averages out the internal variations, leaving only the forced climate variability (e.g., CO₂ forcing). With most of the modern warming beginning in the late 1970's, the recent 50-year warming is on the same time scale as the multi-decadal oscillations of the AMO and PDO.

Here are summary statements from the IPCC AR5 and AR6 reports:

“Decadal variability in the Pacific, associated with the PDO or IPO, contributes significantly to regional and global temperature trends, but the relative contributions of internal variability and external forcing are difficult to disentangle in CMIP5 simulations.” (IPCC, 2013)

"Since AR5, there has been increased understanding of the role of internal variability, such as ENSO, PDO, and AMO, in modulating regional climate trends. However, limitations in simulating the exact timing and amplitude of these modes in CMIP6 models contribute to uncertainties in attributing observed changes to anthropogenic forcing (high confidence)." (IPCC, 2021)

The amplitude of the peak-to-trough impact of the multi-decadal oscillations on global temperatures has been assessed by the IPCC AR6: “The likely range of change due to internal variability is -0.2°C to +0.2°C (IPCC, 2021).” This implies a trough-to-peak change of 0.4°C. Over many centuries, any global temperature changes from the troughs and peaks will cancel out, with little to no net impact.

However, with a nominal timescale of 60-80 years for oscillations such as the AMO and PDO, the timing of the peaks and troughs can be confused with the secular trend. This becomes very relevant for attributing the warming for the 50 years since 1975, during which most of the warming has occurred. Even if climate models have the correct amplitude of the multidecadal oscillations, the timing of the peaks and troughs is not adequately simulated, with each model and individual

ensemble simulating a different phasing. Once the simulations of the ensemble members and different models are averaged, the natural internal variability contribution is averaged out, effectively cancelling the role of natural internal variability in the attribution process.

The Great Pacific Climate Shift of 1976-1977 was a notable climatic event characterized by an abrupt change in the North Pacific Ocean's atmosphere-ocean system that interacted with global climate patterns. This shift is closely associated with the Pacific Decadal Oscillation (PDO) that oscillates between warm and cool phases over decades. The 1976 shift marked a transition from a predominantly negative (cool) PDO phase (1947–1976) to a positive (warm) phase (1977 through 2000), with significant implications for global and regional climate patterns including the frequencies of El Nino and La Nina events. The Great Pacific Climate Shift coincided with the beginning of a period of accelerated global warming (REF TO A FIG OF GLOBAL TEMP ANOMALIES ELSEWHERE IN DOC) When the Great Pacific Climate Shift is accounted for in climate attribution analyses since 1950, it has been found that 40 percent or more of the warming in the second half of the 20th century was caused by natural internal variability (McLean et al., 2009; Tung and Zhou, 2013; Chylek et al., 2016; Scafetta, 2021).

7.3.2 Optimal fingerprinting

Optimal fingerprinting is a statistical technique introduced by Allen and Tett (1999) that compares observed climate data to climate model simulations to identify patterns (or "fingerprints") associated with human or natural forcing. It involves taking a vector of observed climate changes, such as warming rates in locations around the world, and decomposing them into a weighted sum of "signals", which are analogues to the observations generated by climate models with different types of forcings. The weights are chosen using a regression method called Total Least Squares. The analysis commonly uses just two signals, one generated by models using only anthropogenic forcings and one using only natural forcings. If the estimated weighting coefficient attached to a signal is significantly different from zero, then that signal is said to be "detected". If it is close to 1.0, then the model generating the signal is said to be consistent with observations. If it is less than 1.0, then the model signal for that forcing is too strong and needs to be scaled down, and vice-versa. Both the observed data and the signals are weighted using a model-generated estimate of patterns of randomness in the climate system so as, in principle, to put maximum weight on regions where natural variability is minimized.

Optimal fingerprinting is the primary tool for attribution in the climate literature. Studies applying it have been cited thousands of times, and it has been prominently featured by the IPCC since the 2001 Third Assessment Report. One of its inherent weaknesses is that results depend on assumptions about the accuracy of climate models, especially regarding their representation of natural variability (IPCC AR5 Ch 10.2.3).

Additionally, a series of papers by McKittrick (McKittrick 2022a, 2022b, 2023, 2025) has challenged the optimal fingerprinting method, arguing that it is inherently unreliable and that commonly used practices in econometrics can provide more valid results. Statistical theory requires that for regression models to yield unbiased coefficients, a set of assumptions called the Gauss-Markov conditions must hold. McKittrick (2022a) argued that the Allen and Tett (1999) methodology violates the Gauss-Markov conditions, leading to potentially biased and inconsistent

fingerprinting coefficients, undermining the reliability of the method. Chen et al. (2023) confirmed this analysis and argued that the method could yield unbiased results but only under very stringent assumptions. McKittrick (2022b) and (2023) raised a further concern that climate scientists—virtually alone among scientific disciplines—have used an estimation method called Total Least Squares (TLS) to estimate anthropogenic greenhouse gas signal coefficients, despite its tendency to be unreliable unless some strong assumptions hold that in practice are unlikely to be true. Under conditions which easily arise in optimal fingerprinting, TLS yields estimates with large positive biases. Thus, any study that has used TLS for optimal fingerprinting without verifying that it is appropriate in the specific data context has likely overstated the result.

McKittrick (2025) presented an empirical example comparing the results of conventional optimal fingerprinting against methods drawn from mainstream econometrics which are known to be valid for the specific application of signal detection. While the IPCC optimal fingerprinting method yields an anthropogenic signal coefficient close to 1.0 on a global temperature data set spanning 1900 to 2010, consistent estimation yields a coefficient around 0.4, which rises to about 0.65 on data spanning 1980 to 2010, implying the model response to greenhouse gases needs to be scaled down by about half to optimally match observations. The natural forcing signal coefficient, by contrast, is between 2.0 and 4.0, implying the climate model signals of natural forcing need to be scaled up two-to four-fold to match observed climate change. The fingerprinting coefficients estimated in McKittrick (2025), when used to scale the average sensitivity of the climate models used to generate the forcing signals in his data set, imply a Transient Climate Sensitivity of 1.4°C, which matches the estimate by Lewis (2022) using a different estimation method and multiple independent data sets.

While these analyses do not prove that all of the results from using the IPCC optimal fingerprinting method are wrong, it does show that the basis on which they were believed to be correct is non-existent – hence reducing confidence in the results.

7.3.3 Time series methods

The IPCC (AR5 WGI 10.2.2) drew attention to alternative approaches of assessing causality that emerged from the time series econometrics literature. They have the advantage of not depending on assumptions about the accuracy of climate models, but their disadvantage is they depend on assumptions about the data generating process underlying climate and forcing data that are not straightforward to test. The methods, now referred to as climate econometrics, use the tools of unit root testing, Granger causality and cointegration analysis, all of which are familiar in economics and finance and which are slowly being adopted in climate science. Time series analysis methods hold out the possibility of determining whether anthropogenic or natural forcings are the primary drivers of climate change without requiring the use of climate models, although key questions remain unsettled (e.g. Dergiades et al. 2016, Balcombe et al. 2019, Dagsvik et al. 2020, Razzak 2022, Dagsvik and Moen 2023).

Granger causality modeling is a tool for determining directions of influence in data series that move together. “Granger causality” is a statistical, not a physical, concept. If knowing the current value of one variable significantly improves the forecast accuracy of another variable we can infer a causal connection exists; this is called Granger causality. The modeling tools, called vector autoregression, measure direct impulse-response patterns and feedbacks. An application to

the well-known Vostok ice core data revealed an error by Al Gore in his documentary *An Inconvenient Truth*. Gore showed the data and drew attention to the coherence of temperature and CO₂ changes over a 440,000 year span, which he asserted was due to CO₂ driving temperature changes. But temperature changes can also affect atmospheric CO₂ levels. Davidson et al. (2015) examined the series and found that temperature Granger causes CO₂ but not the reverse. In other words on the time scales represented in the Vostok data the coherence in the series is primarily due to the influence of temperature on CO₂ levels not the feedback going from CO₂ to temperature.

In summary, the main statistical methods for attributing causation in climate data are optimal fingerprinting and time series analysis. Applications of the Allen and Tett (1999) optimal fingerprinting method dominate the attribution literature and have underpinned past IPCC conclusions, but results depend on the accuracy of climate models and the method has recently been criticized as inherently biased. Time series methods do not depend on climate models but require assumptions of their own and have generated results that have thus far not converged on a consensus.

7.4 Extreme event attribution (EEA)

The IPCC AR6 provides an ambiguous assessment of the role of global warming in the historical record of extreme weather and climate events. Chapter 11 of WG1 states (Seneviratne et al., 2021):

“Evidence of observed changes in extremes and their attribution to human influence (including greenhouse gas and aerosol emissions and land-use changes) has strengthened since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes (including dry/hot events and fire weather). Some recent hot extreme events would have been extremely unlikely to occur without human influence on the climate system.”

By contrast, Chapter 12 of WG1 (Table 12.12) paints a different picture – presumably, the expert judgment of different groups of authors for the two chapters came to different conclusions (Ranasinghe, 2021):

- High confidence in an increase in extreme heat events in tropical regions where observations allow trend estimation and in most regions in the mid-latitudes, medium confidence elsewhere
- Medium confidence in a decrease in extreme cold events in Australia, Africa and most of northern South America where observations allow trend estimation
- No evidence of emergence in the historical period of a change in river floods, heavy precipitation, drought, fire weather, severe wind storms, and tropical cyclones

While the overall issue of detecting changes in extreme weather events and their attribution remains ambiguous, most of the activity in this area relates to the attribution of single extreme weather events. The most prominent effort is the World Weather Attribution (WWA; worldweatherattribution.org), which is an international research initiative that focuses on extreme event attribution analyzing how climate change influences the likelihood and intensity of extreme weather events. The approach used by the WWA runs large ensembles of regional climate models

to compare the event in today's climate, versus a pre-industrial counterfactual climate without human-caused warming.

WWA plays a prominent role in linking extreme weather to climate change and its press releases attract considerable public and policy discussions. However, the WWA's tendency to promote non-peer-reviewed findings, funding ties, open admission that they shape their analyses to serve purposes of litigation and other methodological challenges have sparked controversies, with critics questioning the robustness and impartiality of its conclusions (Pielke Jr. 2024). Despite these issues, WWA's work continues to shape climate science and media narratives. Technical criticisms of the approach include: neglect of a formal detection process; an implicit assumption that 100% of the post-industrial warming is caused by CO₂; and failure to adequately account for natural internal climate variability.

Because EEA is relatively new many basic methodological issues have yet to be settled in the expert literature. An important challenge is the lack of data. Extreme events are by definition rare. Many analyses of extreme event types (including the US National Assessment Reports) only evaluate data since 1950 or 1970. However, as emphasized by Chapter 8, many of the worst extreme weather and climate events in U.S. history occurred prior to the first half of the 20th century including in the early 19th century. And if paleoclimate reconstructions are considered, it becomes very difficult for an event to pass the detection thresholds of exceeding what is expected from natural variability, particularly if a reasonably sized geographic region is considered.

Another challenge is defining the event under study. There is a longstanding literature in statistics and econometrics on the challenge of analyzing data with outliers. The issue arises because a data series establishes a probability distribution defining the expected range of observations. If an outlier is observed it might indicate that the underlying process giving rise to the data distribution has changed (which in the weather context would mean a climatic change has been detected) or that the underlying process has multiple regimes each with a different probability distribution, in which case observing an outlier simply means we were temporarily in a different regime, but the system itself was unchanged. If a time series contains only a single outlier event at the end of the series it is not possible to determine which model is the correct one (Chen and Liu 1993). For instance, there might be an "ordinary" weather regime that yields a distribution of summer daytime highs in a particular coastal region, and a second "heatwave" regime that kicks in when an inland blocking event occurs, which yields a temperature distribution centered 15°C higher than the first one. A day with temperatures 13°C above normal would either be an extreme heat anomaly under the first regime or a somewhat cool event under the second, and we have no way in this case of knowing on statistical grounds which view is correct.

Visser and Petersen (2012) and Sardeshmukh et al. (2015) both point out that different distributions may fit observed data equally well but yield very different implications about the likelihood of a specific weather event. Visser and Petersen argue that, in view of the deep uncertainties of extreme weather analysis drawing a connection between individual events and global climate change should be avoided. Furthermore the existence of an outlier at the end of a data series poses the problem that estimates of the event probabilities will be biased whether the outlier is included or excluded (Barlow et al. 2020). Methods to eliminate the bias have not yet been established, leading some experts (e.g. Miralles and Davison 2023) to argue that in settings in which a data series

contains a single extreme event at the end, estimation of a return period for the extreme event will be so biased and uncertain it should be avoided altogether.

In spite of these concerns, the U.S. is presently considering something like the WWA, which is being investigated by a NASEM Panel on Attribution of Extreme Weather and Climate Events and their impacts (NASEM, 2025).

A case studies from a recent high impact extreme events in the U.S. is provided to illustrate the challenges and ambiguities in attributing the frequency and intensity of extreme weather events to human-caused warming.

7.4.1 Case study – 2021 Western North America heat wave

The 2021 Western North America heat wave was an extreme heat wave that affected much of Western North America in late June 2021. In particular, surface temperature records were set in Portland, OR (116°F; previous record 107°F) and Seattle, WA (108 °F; previous record 103°F) (Mass et al., 2024).

The WWA team garnered international headlines for their analysis and provided the following attribution statements (WWA, 2021; Philip et al., 2022):

- Based on observations and modeling, the occurrence of this heatwave was virtually impossible without human-caused climate change.
- The event is estimated to be about a 1 in 1000-year event in today's climate.
- The event would have been at least 150 times rarer without human-induced climate change.
- This heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution (when global mean temperatures were 1.2°C cooler than today).

But an important caveat to the first claim is that other researchers concluded, based on historical weather data, that while a heat wave of the magnitude observed was indeed virtually impossible without anthropogenic climate change, it was also virtually impossible *with* climate change. Bercos-Hickey (2022) noted “these temperatures were virtually impossible under any previously experienced meteorological conditions, with or without global warming.” McKinnon and Simpson (2022) stated “the most likely explanation remains that the weather event itself was ‘bad luck.’” The 2023 Oregon Climate Assessment (Fleischman 2023) concluded that the heat dome would have formed even without climate change and “There is no evidence that the highly unusual combination of weather features that drove the heat dome were made more likely by climate change, and climate models do not project an increase in the frequency of high-pressure ridges over the Pacific Northwest” (Fleischman 2023 p. 49).

Mass et al. (2024) summarizes the proximate sequence of compound events leading to the heat wave. There was a record-breaking midtropospheric ridge over the Pacific Northwest, forced by a tropical disturbance in the western Pacific. This produced record-breaking midtropospheric temperatures, strong subsidence in the lower atmosphere, low-level easterly flow that produced downslope warming on regional terrain and the removal of cooler marine air, and an approaching

low-level trough that enhanced downslope flow. The event occurred at a time of maximum solar insolation, and drier-than-normal soil moisture. Using a storyline approach, Mass et al. assessed that there is no trend in drought and dry soils in the Pacific Northwest; there is no evidence of global warming producing stronger ridges of high pressure, and no observed trend in heat waves or record temperatures in the region. They concluded that although anthropogenic warming may have contributed as much as 2°F to the magnitude of the event, there is little evidence of further amplification of the event from increasing greenhouse gases.

A statistical analysis of a model-based attribution study of this heat wave was conducted by Bercos-Hickey et al. (2022). Because this event is a far outlier and far above the bounds of Generalized Extreme Value distributions fitted from historical data, they concluded that estimates of return times, quantitative changes in event magnitude and frequency, and probability of the extreme temperatures such as provided by the WWA are not accurate and should be interpreted as having low confidence. They found that hindcast attribution methods using an ensemble of regional climate models, combined with Pearl (2009) causal inferences, can provide limited and conditional information about the magnitude of the human influence on this heatwave – they provided a more highly constrained estimate that human activities caused a ~1.4°C–1.8°F increase in the daily maximum temperatures.

Zeder et al. (2023) also concluded that the methods employed by Philip et al. (2022) tend to overstate the rarity of extreme heat waves, leading to a biased perception of the effect of climate change on the heatwave event: “The tendency to overestimate the return period of observed extreme heatwave events may fuel the impression that seemingly impossible heatwave extremes are currently clustering at an unprecedented rate.”

The 2021 Western North America heatwave was a rare and unprecedented compound weather event, that broke century-old temperature records by as much as 9°F. While the WWA team received worldwide publicity for their rapid attribution claims blaming anthropogenic climate change, subsequent peer-reviewed analysis showed that the rare event was not made more probable by global warming.

7.5 Summary

There is an ongoing scientific debate around attribution methods, particularly in attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement.

There are two areas of substantive criticism of the IPCC assessment of the causes of the recent warming: inadequate assessment of natural climate variability, and inappropriate statistical methods.

Detection of extreme weather events is challenged by their rarity, requiring a long data set and a choice of region and spatial scale to evaluate their occurrence against the background of natural weather and climate variability.

The most robust attribution statements for an extreme event relate to an incremental change (e.g. a temperature change in degrees or percent change in rainfall). Statements related to return times, quantitative changes in event magnitude and frequency, and probability of the extremes are not accurate owing to an inadequate amount of data, and are made with low confidence. There is no evidence in a change of weather or climate regime patterns from increasing greenhouse gases that would amplify or dampen extreme weather events, beyond basic thermodynamic considerations.

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Bercos-Hickey et al. (2022) Anthropogenic Contributions to the 2021 Pacific Northwest Heatwave. *Geophysical Research Letters* 49 <https://doi.org/10.1029/2022GL099396>

Pielke Jr., Roger (2024) Weather Attribution Alchemy. Substack essay <https://rogerpielkejr.substack.com/p/weather-attribution-alchemy>

From: Judith Curry [curry.judith@gmail.com]
Sent: 5/9/2025 6:39:16 PM
To: Steven Koonin [steven.koonin@gmail.com]
CC: Roy Spencer [roywspencer@hotmail.com]; John Christy [climatemanager60@gmail.com]; Ross McKittrick [ross.mckittrick@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]
Subject: Re: attribution chapter

OOPs, previous email is the climate sensitivity chapter.

New attribution chapter coming in next email

On Fri, May 9, 2025 at 11:34 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Judy – your email text says “attribution chapter” but you attached chapter 5 (climate sensitivity). Can you straighten out the confusion?

SEK

From: Judith Curry <curry.judith@gmail.com>
Sent: Friday, May 9, 2025 12:27 PM
To: Roy Spencer <roywspencer@hotmail.com>; John Christy <climatemanager60@gmail.com>; Steve Koonin <steven.koonin@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>
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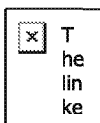
Latest version of attribution chapter is attached, Ross and I have hashed through this pretty thoroughly, we look forward to your comments

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curry.judith@cfanclimate.com | +1.404.803.2012
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Sent: Sunday, May 18, 2025 8:48 AM
To: John Christy
Cc: Judith Curry; Steve Koonin; Roy W. Spencer; Ross McKittrick
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I like the last paragraph about the preliminary nature of this report.

John Christy
Director, Earth System Science Center
Professor, Atmos and Earth Science
Alabama State Climatologist
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climateman60@gmail.com

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From: Roy Spencer <roywspencer@hotmail.com>
Sent: Sunday, May 18, 2025 10:16 AM
To: Travis Fisher; John Christy
Cc: Judith Curry; Steve Koonin; Ross McKittrick
Subject: Re: Authors' preface?

My first impression is that it would be inviting ridicule to mention personal politics, no matter how conservationist or "green".

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From: Ross McKittrick <ross.mckitrick@gmail.com>
Sent: Sunday, May 18, 2025 12:07 PM
To: Judith Curry
Cc: Roy Spencer; Travis Fisher; John Christy; Steve Koonin
Subject: Re: Authors' preface?

We have a Foreword already that explains a bit about how the project began and states that we wrote without editorial oversight. In general I would say that with the Preface or Foreword, less is more. We especially need to avoid anything that strikes a defensive tone or makes it sound like we're looking for establishment approval. While we might be in for a pleasant surprise in that regard, we shouldn't be under any illusions.

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Cc: Steve Koonin; Roy W. Spencer; Ross McKittrick; Travis Fisher
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Sent: 8/14/2025 6:52:26 PM
To: Steven Koonin [steven.koonin@gmail.com]
CC: Judith Curry [curry.judith@gmail.com]; John Christy [climatemanager60@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]
Subject: Re: Carbon brief

I assume this is a preview of what we'll face in the public review comments. Some overlap with the internal DoE comments.

If we were asked to respond to Carbon Brief I'd say something like this:

We are going through these comments, which we hope will be submitted to the public docket so that our responses will also be on the public record. In many cases the comment authors ask for more context or acknowledgment of conflicting evidence. There are some specific allegations of inaccuracies or incorrect citations and we will check those especially carefully.

On Thu, Aug 14, 2025 at 2:36 PM Steven Koonin <steven.koonin@gmail.com> wrote:

If we do respond to each comment, we should request that Carbon Brief post the response. But would they agree to that?

From: Judith Curry <curry.judith@gmail.com>
Sent: Thursday, August 14, 2025 2:29 PM
To: Steven Koonin <steven.koonin@gmail.com>
Cc: John Christy <climatemanager60@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>
Subject: Re: Carbon brief

THX. I think we should respond to this. Some are substantive, but most can be dealt with as suggested by Steve. I have time to start going through this

On Thu, Aug 14, 2025 at 11:12 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Word doc attached

[I printed the website page from my Chrome browser to a pdf file, then converted the pdf to Word]

SEK

From: Judith Curry <curry.judith@gmail.com>
Sent: Thursday, August 14, 2025 1:56 PM
To: John Christy <climatemanager60@gmail.com>
Cc: Steven Koonin <steven.koonin@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Roy W. Spencer

<roywspencer@hotmail.com>

Subject: Re: Carbon brief

I tried to make a .doc file out of the carbon brief thing, but i could only get this crazy 5 column illegible thing. If no one else can figure this out, i can do a tedious cut and paste of a pdf into .doc

On Thu, Aug 14, 2025 at 10:42 AM John Christy <climateman60@gmail.com> wrote:

My, that's a clever way to present the results. I suppose we can look at them as "public comments" and address as needed.

John C.

On Thu, Aug 14, 2025 at 12:33 PM Judith Curry <curry.judith@gmail.com> wrote:

carbon brief fact check is now up

<https://interactive.carbonbrief.org/doe-factcheck/index.html>

On Thu, Aug 14, 2025 at 10:26 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Looking now myself at the bios, I expect the focus will be impacts on public health and on ecosystems. As Judy notes, only 3 with backgrounds that would let them look critically at physical climate science.

Health impacts of local pollutants are obvious; of CO2-induced temperature rise, not so much.

From: Judith Curry <curry.judith@gmail.com>

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To: Steven Koonin <steven.koonin@gmail.com>

Cc: Ross McKittrick <ross.mckittrick@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>

Subject: Re: NAS committee membership posted

i read the bios, very much focused on energy and the environment (only 3 climate scientists)

Not clear what angle they will take on their report

On Thu, Aug 14, 2025 at 7:20 AM Steven Koonin <steven.koonin@gmail.com> wrote:

<https://www.nationalacademies.org/our-work/anthropogenic-greenhouse-gases-and-us-climate-evidence-and-impacts#sectionCommittee>

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+1.404.803.2012
<http://www.cfanclimate.net>

From: Roy Spencer <roywspencer@hotmail.com>
Sent: Thursday, August 14, 2025 2:52 PM
To: Steven Koonin; 'Ross McKittrick'
Cc: 'Judith Curry'; 'John Christy'
Subject: Re: Carbon brief

Greening might be attacked the most because (1) it's easy for the public to understand, and (2) it is difficult to refute, yet it must be refuted because increasing CO2 must NOT be allowed to have any benefits.
-Roy

From: Steven Koonin <steven.koonin@gmail.com>
Sent: Thursday, August 14, 2025 1:34 PM
To: 'Ross McKittrick' <ross.mckittrick@gmail.com>
Cc: 'Judith Curry' <curry.judith@gmail.com>; 'John Christy' <climateman60@gmail.com>; 'Roy W. Spencer' <roywspencer@hotmail.com>
Subject: RE: Carbon brief

Scanning a bit more thoroughly now, it seems that our discussion of greening and TSI drew the most criticisms. We may need to enlist some of the primary TSI authors we cite (Soon?) to help with a rebuttal. Haven't yet dug deeply enough into the greening critiques.

SEK

From: Ross McKittrick <ross.mckittrick@gmail.com>
Sent: Thursday, August 14, 2025 2:20 PM
To: Steven Koonin <steven.koonin@gmail.com>
Cc: Judith Curry <curry.judith@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>
Subject: Re: Carbon brief

Out of 150 pages they show 18 pages where an allegedly false claim is made. In many of these (and the beige) cases the quoted expert merely wants more context. Lots of griping about the discussion of solar reconstructions, and lots of claims that the IPCC does indeed discuss CO2 fertilization more than we give them credit for. And lots of griping that, sure CO2 benefits plants but the warming will harm them.

There are a few comments that point to genuine errors but these should be easy to address. Considering the scope of their investigation there are a lot of report sections where they evidently did not get any negative feedback. Too bad they didn't quote any of the authors who supported what we wrote.

On Thu, Aug 14, 2025 at 1:59 PM Steven Koonin <steven.koonin@gmail.com> wrote:

I expect a lot of this will be easy to respond to. Here's the first comment (I've not read beyond it) and a tentative response:

MISLEADING

The growing amount of CO2 in the atmosphere directly influences the Earth system by promoting plant growth (global greening), thereby enhancing agricultural yields, and by neutralising ocean alkalinity.

Anonymous

This ignores other effects of rising CO2 concentrations, i.e.: on climate. It is also failing to mention that increased CO2 can reduce the nutrient density of some crops.

Response: The report does not ignore the other effects of rising CO2 concentrations – in fact, the great bulk of the report is concerned with exactly that. And the report does mention the possible reduction in nutrient density (insert citation to the CWG report page)

[The criticism is rather silly. It could equally be leveled at the statement "CO2 is changing the climate" because it omits the fact that CO2 enhances plant growth.]

SEK

From: Judith Curry <curry.judith@gmail.com>

Sent: Thursday, August 14, 2025 1:47 PM

To: John Christy <climateman60@gmail.com>

Cc: Steven Koonin <steven.koonin@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>

Subject: Re: Carbon brief

Well there is a lot of meat in these comments, but most are claims of "misleading" by authors who wanted to make a different point. But worth going through carefully

On Thu, Aug 14, 2025 at 10:42 AM John Christy <climateman60@gmail.com> wrote:

My, that's a clever way to present the results. I suppose we can look at them as "public comments" and address as needed.

John C.

On Thu, Aug 14, 2025 at 12:33 PM Judith Curry <curry.judith@gmail.com> wrote:

carbon brief fact check is now up

<https://interactive.carbonbrief.org/doe-factcheck/index.html>

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Health impacts of local pollutants are obvious; of CO2-induced temperature rise, not so much.

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Sent: Thursday, August 14, 2025 10:57 AM

To: Steven Koonin <steven.koonin@gmail.com>

Cc: Ross McKittrick <ross.mckittrick@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>

Subject: Re: NAS committee membership posted

i read the bios, very much focused on energy and the environment (only 3 climate scientists)
Not clear what angle they will take on their report

On Thu, Aug 14, 2025 at 7:20 AM Steven Koonin <steven.koonin@gmail.com> wrote:

<https://www.nationalacademies.org/our-work/anthropogenic-greenhouse-gases-and-us-climate-evidence-and-impacts#sectionCommittee>

Steven Koonin

--

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curry.judith@cfanclimate.com | +1.404.803.2012
<http://www.cfanclimate.net>

From: Ross McKittrick [ross.mckittrick@gmail.com]
Sent: 8/14/2025 6:19:35 PM
To: Steven Koonin [steven.koonin@gmail.com]
CC: Judith Curry [curry.judith@gmail.com]; John Christy [climatemanager60@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]
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Steven Koonin

--



Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA

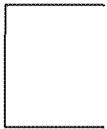
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Sent: Thursday, August 14, 2025 1:59 PM
To: Judith Curry
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Subject: Re: Carbon brief

It would be a new approach to identify "Carbon Brief_Author" as a source of public comments and directly address them. They want to do science in the press, we want to do science in an organized, dispassionate manner.

John C.

On Thu, Aug 14, 2025 at 12:56 PM Judith Curry <curry.judith@gmail.com> wrote:

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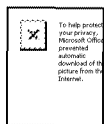
Steven Koonin

--



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<http://www.cfanclimate.net>

From: John Christy <climateman60@gmail.com>
Sent: Thursday, July 31, 2025 1:05 PM
To: Ross McKittrick
Cc: Steven Koonin; Roy W. Spencer; Judith Curry; Josh Loucks; Seth Cohen; Travis Fisher
Subject: Re: Carbon Brief factcheck - your study has been cited in new US DoE 'critical review'

Cliff Mass just received the Carbon Brief questionnaire, but I haven't even though my papers are cited.

On Thu, Jul 31, 2025 at 11:44 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

I knew Zeke would object to that. They buried the key figure in the online appendix. We can cite the main part of their discussion (one of the DoE reviewers brought this up too) but it doesn't change the findings in question.

On Thu, Jul 31, 2025 at 12:38 PM Steven Koonin <steven.koonin@gmail.com> wrote:

Zeke H's complaint is that we used a figure from one of his papers to make a different point than his paper did.

No foul in that and shame on him if he missed the point we made.

If all the complaints are of that quality...

Steven E. Koonin

On Jul 31, 2025, at 10:27, Ross McKittrick <ross.mckittrick@gmail.com> wrote:

John and I got this from Tim Vogelsang at MSU. Carbon Brief is contacting everyone whose work was cited trying to gather up claims of misrepresentation. As Tim notes, there is no option on the form for saying your work was correctly characterized.

From: Vogelsang, Timothy <tjv@msu.edu>
Sent: Thursday, July 31, 2025 12:19 PM
To: Ross McKittrick <rmckitri@uoguelph.ca>; John Christy <climateman60@gmail.com>
Subject: RE: Carbon Brief factcheck - your study has been cited in new US DoE 'critical review'

CAUTION: This email originated from outside of the University of Guelph. Do not click links or open attachments unless you recognize the sender and know the content is safe. If in doubt, forward suspicious emails to IThefp@uoguelph.ca.

If you look at the pdf I was sent with the instructions, there is no option to report that someone's research has been correctly characterized. That's not a very scientific factchecking exercise, is it!

Tim

From: Ross McKittrick <rmckitri@uoguelph.ca>
Sent: Thursday, July 31, 2025 12:15 PM
To: Vogelsang, Timothy <tjv@msu.edu>; John Christy <climateman60@gmail.com>
Subject: Re: Carbon Brief factcheck - your study has been cited in new US DoE 'critical review'

I've heard of Carbon Brief but only read snippets of their articles cited elsewhere. They seem to be heavily into promoting renewables.

It's interesting to watch the machine swing into gear. There is a public comment docket opening up and I expect there will be quite the avalanche of material submitted, which we will need to prepare responses to, all of which will form part of the public record. If the comments are substantive we'll readily make revisions. We responded to a lot of comments from the internal DoE staff during the pre-publication review stage. But some of the most hostile comments didn't provide any data or citations in support so we couldn't do anything with them.

Ross

Dr. Ross McKittrick

Professor of Economics

Department of Economics and Finance

rossmckitrick.com

<image001.png>

University of Guelph | Guelph ON Canada N1G 3P9

From: Vogelsang, Timothy <tjv@msu.edu>
Sent: Thursday, July 31, 2025 12:02 PM
To: Ross McKittrick <rmckitri@uoguelph.ca>; John Christy <climateman60@gmail.com>
Subject: FW: Carbon Brief factcheck - your study has been cited in new US DoE 'critical review'

CAUTION: This email originated from outside of the University of Guelph. Do not click links or open attachments unless you recognize the sender and know the content is safe. If in doubt, forward suspicious emails to IThep@uoguelph.ca.

Ross and John,

I just got this email. Maybe you know about this group. I'm sure this is just the tip of the iceberg of pushback coming.

Tim

From: Leo Hickman <leo.hickman@carbonbrief.org>
Sent: Thursday, July 31, 2025 11:49 AM
To: Leo Hickman <leo.hickman@carbonbrief.org>
Subject: Carbon Brief factcheck - your study has been cited in new US DoE 'critical review'

Hello,

I'm contacting you because we have noticed that at least one of your studies has been cited in a new report published this week by the US Dept of Energy titled, "A Critical Review of Impacts of Greenhouse Gas Emissions on the U.S. Climate."

A number of scientists cited in the report have already publicly highlighted that their findings have been falsely or misleadingly characterised. It seems that the report is intended to be used as scientific justification by the Trump administration in its efforts to revoke the US Environmental Protection Agency's "endangerment finding" on greenhouse gases.

Carbon Brief is now seeking your help to assess whether your own study, or indeed your area(s) of expertise more widely, have been mischaracterised in the report. This is part of a wider 'crowdsourced' fact-checking effort we are now convening to draw on inputs from experts in their respective fields.

I have attached a PDF with some instructions on how you can participate with your own insights and reflections, should you wish. (The instructions include ways to do this anonymously and securely, if that is your preference.)

Additionally, if you know of a colleague or co-author who might wish to participate, please feel free to forward this email to them.

Our deadline for submissions is Monday 11 August 2025 - 0900 GMT.

Many thanks in advance.

Best wishes, Leo

--

Leo Hickman

Editor, Carbon Brief

Phone: + 44 (0) 7731 403979

Social: Twitter; BlueSky: LinkedIn

Web: www.carbonbrief.org

Need a digest of the latest climate change-related headlines sent to your inbox? You can sign up to Carbon Brief's free daily, weekly, Cropped and China Briefing newsletters [here](#).

From: N H Lewis <nhlewis@btinternet.com>
Sent: Wednesday, August 13, 2025 4:21 AM
To: 'Judith Curry'; 'Ross McKittrick'; 'John Christy'; 'Roy Spencer'; 'Steven Koonin'
Cc: nhlewis@btinternet.com
Subject: RE: Carbon Brief factcheck - your study has been cited in new US DoE 'critical review'

Dear All

You cited in chapter 4 of your DoE report the preprint of my Comment on Sherwood & Forest's 2024 ACP piece on climate sensitivity. I am pleased to say that the final version of my Comment has today been published in ACP, [here](#). Thanks to a detailed public comment by Steven Sherwood on my manuscript (which was treated as obviating the need for a second anonymous peer review: see [here](#)), I was able to make my comment considerably more extensive. Steven's understanding both of Lewis (2022) and of statistical aspects of Sherwood et al (2020) appears limited.

FYI, I submitted very favourable comments to The Associated Press on your DoE report. I have not responded to the Carbon Brief email. As you may be aware, although it is called a 'Fact check', the only ratings allowed for points being checked are False or Misleading – hardly unbiased!

All the best,
Nic

From: N H Lewis [mailto:nhlewis@btinternet.com]
Sent: 06 August 2025 15:43
To: 'Judith Curry'; 'Ross McKittrick'; 'John Christy'; 'Roy Spencer'; 'Steven Koonin'
Cc: 'nhlewis@btinternet.com'
Subject: FW: Carbon Brief factcheck - your study has been cited in new US DoE 'critical review'

Dear All

I expect that you are all aware of Carbon Brief's activities in relation to your recent DOE Climate Working Group review report, but just in case you aren't here is a copy of their recent email, presumably sent to all climate scientists with papers cited in your report.

I've now had a similar email from Michael Phillis at The Associated Press (copy attached). He and their Seth Borenstein have decided to ask a number of questions of the authors of every science-oriented reference in both the actual EPA proposal and the Department of Energy Climate Working Group's review report about the EPA's proposed rescinding the 2009 Endangerment Finding.

All the best,
Nic

From: Leo Hickman [mailto:leo.hickman@carbonbrief.org]
Sent: 05 August 2025 13:23
To: Leo Hickman
Subject: Carbon Brief factcheck - your study has been cited in new US DoE 'critical review'

Hello,

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Many thanks in advance.

Best wishes, Leo

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Leo Hickman

Editor, [Carbon Brief](#)

Phone: + 44 (0) 7731 403979

Social: [Twitter](#); [BlueSky](#); [LinkedIn](#)

Web: www.carbonbrief.org

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From: Judith Curry [curry.judith@gmail.com]
Sent: 8/14/2025 10:38:12 PM
To: Steven Koonin [steven.koonin@gmail.com]
CC: Roy Spencer [roywspencer@hotmail.com]; Ross McKittrick [ross.mckittrick@gmail.com]; John Christy [climateman60@gmail.com]
Subject: Re: Carbon brief
Attachments: Factcheck_Carbon Brief clea.pdf

Attached is a cleaner version of the msword version that Steve sent.

Solar is another topic that got alot of comments. I suggest i collect the relevant comments and send to soon and Connolly for their input

On Thu, Aug 14, 2025 at 1:16 PM Steven Koonin <steven.koonin@gmail.com> wrote:
I'm (probably) onboard with that as well, but will want to review that entire paragraph.

From: Roy Spencer <roywspencer@hotmail.com>
Sent: Thursday, August 14, 2025 3:35 PM
To: Judith Curry <curry.judith@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>
Cc: Steven Koonin <steven.koonin@gmail.com>; John Christy <climateman60@gmail.com>
Subject: RE: Carbon brief

I agree.

-Roy

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Judith Curry <curry.judith@gmail.com>
Date: 8/14/25 2:28 PM (GMT-06:00)
To: Ross McKittrick <ross.mckittrick@gmail.com>
Cc: Steven Koonin <steven.koonin@gmail.com>, John Christy <climateman60@gmail.com>, "Roy W. Spencer" <roywspencer@hotmail.com>
Subject: Re: Carbon brief

There are alot of negative comments also on ocean alkalinity, i think we should take out the statement from acidic ocean in previous cons

On Thu, Aug 14, 2025 at 12:07 PM Ross McKitrick <ross.mckitrick@gmail.com> wrote:

Yes we need to go through them all. And there will be many that, once we've dealt with them, will prove to have been helpful.

On some topics, like albedo, the "beige" comments are actually supportive even though they are promoted as evidence of "misleading" content. E.g. "yes what they say is true but we shouldn't throw out the climate models over this".

On the greening and solar stuff I think we can add references/discussion of the counterevidence without detracting from our main points. At worst they become merely neutral points of discussion. And tbh both those sections are inessential to the report as a whole. So if they absorb a lot of the incoming flak that's just as well.

RPJr has tweeted out about the CB piece that they totally ignored all his comments. No surprise.

On Thu, Aug 14, 2025 at 2:55 PM Judith Curry <curry.judith@gmail.com> wrote:

this statement is fine, but internally i think we need to go through each of these carefully and at the very least add some more references

On Thu, Aug 14, 2025 at 11:52 AM Ross McKitrick <ross.mckitrick@gmail.com> wrote:

I assume this is a preview of what we'll face in the public review comments. Some overlap with the internal DoE comments.

If we were asked to respond to Carbon Brief I'd say something like this:

We are going through these comments, which we hope will be submitted to the public docket so that our responses will also be on the public record. In many cases the comment authors ask for more context or acknowledgment of conflicting evidence. There are some specific allegations of inaccuracies or incorrect citations and we will check those especially carefully.

On Thu, Aug 14, 2025 at 2:36 PM Steven Koonin <steven.koonin@gmail.com> wrote:

If we do respond to each comment, we should request that Carbon Brief post the response. But would they agree to that?

From: Judith Curry <curry.judith@gmail.com>

Sent: Thursday, August 14, 2025 2:29 PM

To: Steven Koonin <steven.koonin@gmail.com>

Cc: John Christy <climateman60@gmail.com>; Ross McKitrick <ross.mckitrick@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>

Subject: Re: Carbon brief

THX. I think we should respond to this. Some are substantive, but most can be dealt with as suggested by Steve. I have time to start going through this

On Thu, Aug 14, 2025 at 11:12 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Word doc attached

[I printed the website page from my Chrome browser to a pdf file, then converted the pdf to Word]

SEK

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To: John Christy <climateman60@gmail.com>

Cc: Steven Koonin <steven.koonin@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>

Subject: Re: Carbon brief

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John C.

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From: Judith Curry <curry.judith@gmail.com>

Sent: Thursday, August 14, 2025 10:57 AM

To: Steven Koonin <steven.koonin@gmail.com>

Cc: Ross McKittrick <ross.mckittrick@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer

<roywspencer@hotmail.com>

Subject: Re: NAS committee membership posted

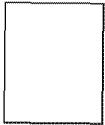
i read the bios, very much focused on energy and the environment (only 3 climate scientists)
Not clear what angle they will take on their report

On Thu, Aug 14, 2025 at 7:20 AM Steven Koonin <steven.koonin@gmail.com> wrote:

<https://www.nationalacademies.org/our-work/anthropogenic-greenhouse-gases-and-us-climate-evidence-and-impacts#sectionCommittee>

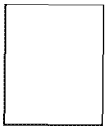
Steven Koonin

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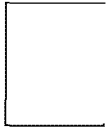
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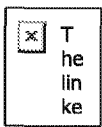
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DOJ 00016139

DOJ_00016142

1. **Definition of global warming**
The term "global warming" refers to the long-term rise in the average temperature of Earth's atmosphere and oceans, which is primarily caused by the increase in greenhouse gas concentrations. This process is driven by human activities, particularly the burning of fossil fuels, which releases large amounts of carbon dioxide and other heat-trapping gases into the atmosphere. These gases trap heat from the sun, leading to a warming effect on the planet's surface and in its atmosphere.

2. **Causes of global warming**
The primary cause of global warming is the increase in greenhouse gas concentrations in the atmosphere. Greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, trap heat from the sun, leading to a warming effect on the planet's surface and in its atmosphere. Human activities, particularly the burning of fossil fuels, are the main source of these gases. Other factors contributing to global warming include deforestation, which reduces the number of trees that can absorb carbon dioxide, and land use changes that alter the Earth's albedo (reflectivity).

3. **Effects of global warming**
Global warming has a wide range of effects on the Earth's climate and environment. It leads to a rise in average temperatures, which can result in more frequent and severe heatwaves, droughts, and wildfires. It also causes the melting of glaciers and ice sheets, leading to a rise in sea levels. This can threaten coastal communities and ecosystems. Additionally, global warming can lead to changes in precipitation patterns, with some areas experiencing more frequent and intense storms and others facing increased drought. The warming of the oceans can also lead to coral bleaching and the loss of marine biodiversity.

4. **Global warming and human health**
Global warming can have direct and indirect effects on human health. Direct effects include the increased frequency and severity of heatwaves, which can lead to heat-related illnesses and deaths, particularly among vulnerable populations such as the elderly and young children. Indirect effects include the impact of global warming on air quality, as higher temperatures can lead to an increase in ground-level ozone and other pollutants, which can exacerbate respiratory conditions. Global warming can also lead to the spread of vector-borne diseases, as warmer temperatures can allow mosquitoes and other insects to thrive in new areas.

5. **Global warming and the environment**
Global warming has a significant impact on the environment, leading to a wide range of ecological changes. It causes the melting of glaciers and ice sheets, which can lead to a rise in sea levels and the loss of habitat for many species. It also leads to the warming of the oceans, which can cause coral bleaching and the loss of marine biodiversity. Global warming can also lead to changes in precipitation patterns, which can affect the availability of water for ecosystems and human use. The warming of the atmosphere can also lead to the expansion of the range of invasive species, which can threaten native biodiversity.

6. **Global warming and the economy**
Global warming can have a significant impact on the economy, leading to a wide range of economic challenges. It can lead to the loss of property and infrastructure due to sea level rise and more frequent and severe storms. It can also lead to the loss of agricultural productivity due to drought and heat stress on crops. Global warming can also lead to increased costs for energy production, as higher temperatures can reduce the efficiency of power plants. The economic impact of global warming is likely to be significant and widespread, affecting many sectors of the economy.

7. **Global warming and society**
Global warming can have a significant impact on society, leading to a wide range of social challenges. It can lead to the displacement of people due to sea level rise and more frequent and severe storms. It can also lead to the loss of livelihoods and the degradation of quality of life due to the impacts of global warming on the environment and the economy. Global warming can also lead to increased social inequality, as vulnerable populations are often the most affected by its impacts. The social impact of global warming is likely to be significant and widespread, affecting many aspects of society.

8. **Global warming and the future**
The future of global warming is uncertain, but it is clear that it is a significant and urgent challenge that we must address. The impacts of global warming are already being felt, and they are likely to become even more severe if we do not take action to reduce greenhouse gas emissions. The future of our planet and our society depends on the actions we take today to address global warming. We must work together to reduce our greenhouse gas emissions and to adapt to the changes that are already underway. Only then can we ensure a sustainable and secure future for all.

DOJ 00016145

Glossary

IPCC: The Intergovernmental Panel on Climate Change, the UN body for assessing the science related to climate change. IPCC works in five-to-eight year cycles and comprises three working groups of scientists, each focusing on different aspects of climate science and the response to climate change. Each assessment cycle, scientists appointed by the IPCC produce three reports summarising the latest climate science, as well as “special reports” and a synthesis report, which serve as key inputs to international climate negotiations.

WG1/2/3: The three working groups of the IPCC. Working Group I (WG1) deals with the physical science basis of climate change, Working Group II (WG2) with climate change impacts, adaptation and vulnerability and Working Group III (WG3) with mitigation of climate change.

AR6: The sixth assessment report of the IPCC, which was published in 2013-14.

AR5: The fifth assessment report of the IPCC, which was published in 2011-12.

CMIP5/6: The Coupled Model Intercomparison Project (CMIP) is the international modelling effort that feeds into the IPCC's influential assessments. CMIP5 was developed for AR5, while CMIP6 was developed for AR6.

Methodology

The DoE report references around 350 sources. Of these, around 240 are peer-reviewed research papers. Other sources include books, commentary articles and letters published in journals, as well as “grey” literature, such as study preprints, blog posts, news articles and government websites.

For this factcheck, Carbon Brief emailed the corresponding authors of all 240 peer-reviewed studies. If the corresponding author did not respond or the email address bounced, Carbon Brief contacted another report author – typically the lead author, if separate to the corresponding author.

In 20 cases, the corresponding author was also an author on the DoE report itself. These authors were not invited to factcheck their own work.

Carbon Brief asked the corresponding authors to read the section of the report that cites their work and to identify if it uses their work to make “misleading” or “false” statements.

False was described as “statements/statistics that are factually incorrect or untrue”.

Misleading was described as “statements/statistics that are presented in a way that distort the meaning, create a false impression or omit/cherry-pick crucial details”.

(Carbon Brief also invited various topic experts to contribute their responses. Respondents were also invited to forward Carbon Brief's request to other experts.)

Carbon Brief's factcheck also includes comments from scientists who have already reacted to the DoE report in public, via media articles, social media or blog posts. Links to these sources are included with the relevant responses.

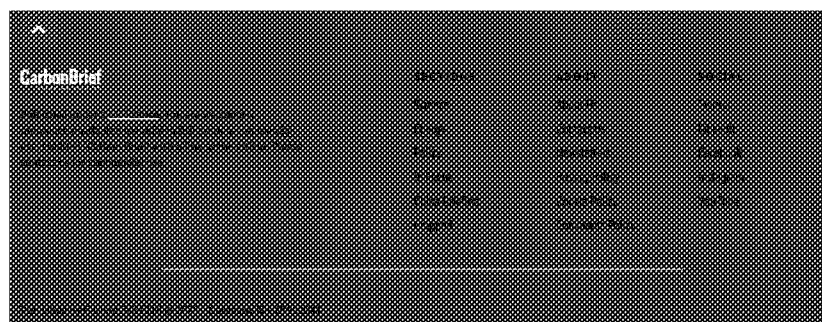
Carbon Brief ensured that any scientists contributing to the factcheck in an anonymous capacity have the appropriate expertise to comment on the sections of the report that they factchecked.

Any pages with “misleading” and “false” statements are shown in orange and red, respectively, in the main graphic. Pages that are not coloured are either accurate, or have not yet been factchecked.

There has been some speculation that artificial-intelligence tools might have been used to generate some parts of the report, particularly the citations, due to some “hallucinatory”-type mistakes. For example, a [Carbon Brief article from 2017](#) is cited, but the credited author is mistakenly listed as another Carbon Brief journalist.

However, Carbon Brief ran samples of the report's main text through several AI text checker tools and found there is a “very low probability” they were generated using AI. It was not possible to do similar checks of the report's citations.

Carbon Brief invites any scientists who notice further errors in the report to email info@carbonbrief.org.



From: Ross McKittrick <ross.mckittrick@gmail.com>
Sent: Wednesday, May 21, 2025 10:03 AM
To: Steven Koonin
Cc: Roy Spencer; Judith Curry; John Christy; Travis Fisher
Subject: Re: carbon cycle revision

That text looks good. This version is now the entry in the post-meeting folder. It also contains Roy's updated scenario figure.

On Wed, May 21, 2025 at 9:10 AM Steven Koonin <steven.koonin@gmail.com> wrote:

The attached contains my revision of the carbon cycle material, section 3.3.2

As I'm somewhat DropBox challenged, I've not posted it, but hope that Ross can incorporate it into the working draft.

Steve Koonin

From: Ross McKittrick [ross.mckittrick@gmail.com]
Sent: 5/9/2025 5:36:52 PM
To: Judith Curry [curry.judith@gmail.com]
CC: Steven Koonin [steven.koonin@gmail.com]; John Christy [climateman60@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]
Subject: Re: ch 11 managing risks of extreme weather
Attachments: 11.Managing Risks.May9[RM].docx

I like the idea of a standalone chapter on risk management, just briefly making the points that resilience has improved over time and the perception of increasing risk has a lot to do with failure to normalize disaster data properly. On which the recent demise of NOAA's BDD series is a good illustration. I added some info on that and reorganized Judy's blurb slightly.

On Thu, May 8, 2025 at 3:58 PM Judith Curry <curry.judith@gmail.com> wrote:
I think each Part needs a bit of a preamble

On Thu, May 8, 2025 at 12:50 PM Steven Koonin <steven.koonin@gmail.com> wrote:
I don't think we need a separate chapter, but this material would fit in well as the beginning of Part III.

From: Judith Curry <curry.judith@gmail.com>
Sent: Thursday, May 8, 2025 3:44 PM
To: Steven Koonin <steven.koonin@gmail.com>
Cc: Ross McKittrick <ross.mckittrick@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>
Subject: ch 11 managing risks of extreme weather

We don't seem to have a chapter for this? I wrote a small blurb for previous (now defunct) chapter, attached. Do we need such a chapter? If so, I could take a crack at this

On Thu, May 8, 2025 at 11:53 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Will do. I also have to finish going through Chapter 6.

SEK

From: Ross McKittrick <ross.mckittrick@gmail.com>
Sent: Thursday, May 8, 2025 2:27 PM
To: Judith Curry <curry.judith@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Steven Koonin <steven.koonin@googlemail.com>
Subject: Ch 7 attribution

Here is a new draft of the attribution chapter. Judy and I did some editing offline for some of the more obscure areas so this version combines our inputs.

I'll post in the Dropbox. Steve maybe you could go through it next.

Ross

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11. Managing risks of extreme weather

11.1 Socioeconomic context

Risks from human-caused climate change are convoluted with natural weather and climate variability, and are dominated by the exposure of wealth in coastal and other disaster-prone regions and vulnerabilities of poorer populations. The evolution of climate risk in the U.S. has been dominated by societal factors, rather than by changes to the actual weather and climate hazards. Deaths from weather disasters have decreased substantially since 1900, even as US population grew from 76 million in 1900 to over 331 million in 2020. For example, the Galveston hurricane killed over 8,000 people in 1900 (0.01% of the US population), whereas the worst recent disaster, Hurricane Katrina in 2005, killed 1800 people (or 0.0006% of the US population).

Technological advances have substantially reduced losses from extreme weather events. Early warning systems, satellite monitoring, and improved weather forecasting have reduced deaths, although exactly numbers are hard to quantify. <https://www.nber.org/papers/w31361> US weather forecasting has been estimated to reduce losses from weather events with an annualized benefit of \$31.5B, protecting lives, property, and supporting agriculture and transportation <https://nap.nationalacademies.org/read/12888/chapter/2> Improved hurricane forecasts have reduced pre- and post-landfall spending, with annual per hurricane cost reductions estimated at \$5B <https://www.nber.org/digest/202409/value-improving-hurricane-forecasts>

Infrastructure improvements have contributed to substantial reductions in losses from extreme weather events. Building codes, such as those implemented in Florida after Hurricane Andrew (1992) have reduced losses by ensuring structures can withstand high winds and floods. Homes built after 2002 showed minimal damage during Hurricane Michael (2018), unlike older homes. <https://www.fema.gov/case-study/role-floridas-building-codes-2018-hurricane-michael> Sea walls, like the Galveston Seawall, protect against wave action and storm surge. The New Orleans Hurricane and Storm Damage Risk Reduction System successfully mitigated storm surge during Hurricane Isaac (2012). Inland dams in the US help control flooding by storing excess water during heavy rains. It is estimated that the Tennessee Valley Authority (TVA) dams prevent about \$309M in annual flood damage in the TVA region and along the Ohio and Mississippi Rivers <https://www.tva.com/environment/managing-the-river/flood-management> During Hurricane Helene (2024), TVA's strategies prevented approximately \$406M in potential damages. <https://www.publicpower.org/periodical/article/tva-flood-mitigation-strategies-prevented-approximately-406-million-potential-damages>

11.2 Data challenges

Since 1980, NOAA has provided a count of annual U.S. weather-related disasters that it estimates to have exceeded \$1Billion (inflation adjusted), showing a substantial increase starting in 2008. NOAA and other government officials have cited the upward trend in the BDD series as evidence that climate change is making extreme weather worse (Pielke Jr.

2024). But over time, population and wealth have increased dramatically in the US, so when an extreme weather or climate event occurs, there is more damage even if there is no underlying trend in the frequency or intensity of extreme weather. A recent estimate finds that losses per weather disaster are down by about 80% since 1980, as a proportion of GDP. <https://drive.google.com/file/d/1MvgwcWaimcn1oHODqNZDG1fXF4M5Idnn/view> Pielke Jr. (2024) argued that in addition to relying on opaque data sources and unreported adjustments NOAA failed to normalize its Billion Dollar Disaster (BDD) data series properly for changes in population exposure and wealth. In May 2025 NOAA announced it has withdrawn the billion dollar disaster product from publication (Pielke Jr. 2025).

In summary, trends in losses from extreme weather and climate events are dominated by population increases and economic growth. Technological advances such as improved weather forecasting and early warning systems have substantially reduced losses from extreme weather events. Better building codes, flood defenses, and disaster response mechanisms have lowered economic losses relative to GDP. And finally, the US economy's expansion has diluted the relative impact of disaster costs, as seen in the comparison of historical and modern GDP percentages.

Pielke Jr., Roger (2024) Scientific integrity and U.S. “Billion Dollar Disasters” *NPJ Natural Hazards* 1 <https://www.nature.com/articles/s44304-024-00011-0>

Pielke Jr., Roger (2025) “RIP NOAA's Billion Dollar Disasters” Substack essay May 8, 2025 <https://rogerpielkejr.substack.com/p/rip-noaas-billion-dollar-disasters>

From: Judith Curry <curry.judith@gmail.com>
Sent: Friday, May 9, 2025 3:06 PM
To: Ross McKittrick
Cc: Steven Koonin; John Christy; Roy W. Spencer; Travis Fisher
Subject: Re: ch 11 managing risks of extreme weather
Attachments: s41467-025-57450-0.pdf

along these lines, a superb new paper has just been published (attached), i could expand on this chapter a bit more if people like the idea of ch 11

On Fri, May 9, 2025 at 10:37 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

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Subject: Ch 7 attribution

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To help protect
your privacy,
Microsoft Office
prevented
automatic
download of this
picture from the
Internet.

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How to stop being surprised by unprecedented weather

Received: 28 June 2024

Accepted: 24 February 2025

Published online: 10 March 2025

 Check for updates

Timo Kelder ^{1,2}, Dorothy Heinrich ^{3,4}, Lisette Klok ¹, Vikki Thompson ⁵, Henrique M. D. Goulart ^{2,6}, Ed Hawkins ⁴, Louise J. Slater ⁷, Laura Suarez-Gutierrez ^{8,9}, Robert L. Wilby ¹⁰, Erin Coughlan de Perez ^{3,11}, Elisabeth M. Stephens ^{3,4}, Stephen Burt ⁴, Bart van den Hurk ⁶, Hylke de Vries ⁵, Karin van der Wiel ⁵, E. Lisa F. Schipper ¹², Antonio Carmona Baéz ¹³, Ellen van Bueren ¹⁴ & Erich M. Fischer ⁸

We see unprecedented weather causing widespread impacts across the world. In this perspective, we provide an overview of methods that help anticipate unprecedented weather hazards that can contribute to stop being surprised. We then discuss disaster management and climate adaptation practices, their gaps, and how the methods to anticipate unprecedented weather may help build resilience. We stimulate thinking about transformative adaptation as a foundation for long-term resilience to unprecedented weather, supported by incremental adaptation through upgrading existing infrastructure, and reactive adaptation through short-term early action and disaster response. Because in the end, we should take responsibility to build resilience rather than being surprised by unprecedented weather.

There are different gradients of extreme weather - from the average hot day to the record-breaking heatwave, from the annual springtime flood to the unprecedented dam breach, from an average tropical cyclone to one occurring after the season is meant to be over. For example, in September 2017, Hurricanes Irma and Maria damaged approximately 95% of the buildings and forced thousands of residents to move into public shelters on the island of Sint Maarten/Saint Martin¹. In neighbouring Puerto Rico, the same hurricanes accounted for more than 4600 deaths, mostly in connection with poor public health infrastructure and essential public services². In 2020, the Horn of Africa recorded its fifth consecutive failed rainy season, with poor pasture conditions, livestock losses, decreased surface water availability and human conflicts, leaving 4.35 million people in need of humanitarian assistance³. In October 2021, severe floods in southwestern Nepal were

unprecedented because they occurred outside of the usual monsoon season, catching warning systems off guard and disrupting agricultural activities, causing over 120 deaths and the displacement of over 4790 families⁴. In July 2021, the Pacific Northwest of North America saw temperatures soar above 45 °C, shattering records for the region. Lytton, BC, Canada, experienced an especially severe spike, with temperatures reaching 49.6 °C, 5.2 °C higher than the previous record set in 1941 from observations dating back to 1917. This event strained the health-care systems and resulted in over 850 deaths⁵. All these events were unprecedented in different ways but had devastating impacts⁶.

It is common to encounter media narratives emphasising the surprise caused by unprecedented weather. Corresponding gaps in disaster preparedness systems and adaptation actions leave communities underprepared and unequipped to handle “surprising” weather events^{6,7}.

¹Climate Adaptation Services Foundation (CAS), Bussum, The Netherlands. ²Institute for Environmental Studies, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands. ³Red Cross Red Crescent Climate Centre, The Hague, The Netherlands. ⁴Department of Meteorology, University of Reading, Reading, UK. ⁵Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands. ⁶Deltares, Delft, The Netherlands. ⁷School of Geography and the Environment, University of Oxford, Oxford, UK. ⁸Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland. ⁹Institut Pierre-Simon Laplace, CNRS, Paris, France. ¹⁰Geography and Environment, Loughborough University, Loughborough, UK. ¹¹Feinstein International Center, Friedman School of Nutrition Science and Policy, Tufts University, Boston, MA, USA. ¹²Department of Geography, University of Bonn, Bonn, Germany. ¹³University of St. Martin (USM), Philipsburg, Sint Maarten. ¹⁴Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands.

 e-mail: timo@climateadaptationservices.com

However, advances in climate science of various kinds are rapidly increasing our understanding of current and future risks of unprecedented weather, and can be used to reduce their impacts by informing disaster management and climate adaptation practices.

The overarching aim of this perspective piece is to argue that we can avoid being surprised by unprecedented weather and ensure that it does not cause unprecedented impacts when it occurs. In this piece, we provide the first comprehensive overview of approaches for analysing unprecedented weather. We then discuss how these approaches can inform disaster management and climate adaptation practices to build resilience to unprecedented weather and ensure that it does not cause unprecedented impacts.

Approaches for analysing unprecedented weather

Approaches to identifying unprecedented weather can be divided into four categories based on the complementary lines of evidence they may provide: conventional methods, past events, event-based storylines, and weather and climate-model data exploration (Fig. 1, Table 1). We refer to Baldisarri Pacchetti et al.⁸ for a discussion on the typology of evidence for regional climate information.

These categories follow a chronological order, starting with conventional methods and studying past events, which have been widely used, and progressing to the more recent approaches from storylines and weather and climate models. Conventional approaches primarily utilise measurements of weather variables. Past events can be based on historical observations, documentary evidence, oral history and proxy data. Event-based storylines can be constructed from a variety of data sources, combining climate modelling with expert judgement, historical observations, proxies, and physical understanding. Weather and climate-model-based approaches depend on the outputs of physics-based models.

These four lines of evidence have specific benefits and limitations, outlined in Table 1.

Conventional statistical approaches using observations

There is a long history of science informing society about extreme weather events that have not been experienced before. Statistical

modelling of extreme values based on weather records became possible around the 1950s⁹. Its use was quickly taken up by engineers for the estimation of flood design values^{10,11}. By the end of the 20th century, weather generators were developed that simulate long synthetic series¹². They have been widely used in engineering design^{13,14}. This section describes these conventional approaches, including their more recent developments.

Extreme value statistics is the conventional method to estimate the probability distribution of extreme events^{9,15}. This method works by choosing an Extreme Value distribution and fitting it to available observational data. Extreme events beyond the observational record can then be estimated by extrapolation, for a given return period, based on the fitted distribution. It is possible to further account for the non-stationarity of the climate system, e.g., in a warming climate, and to estimate how the statistics of extreme events have changed with time or global temperature¹⁶. The benefit of extreme value statistics is that this approach has been widely tested, used, and adopted for estimating design values. The strength of the approach using observations is that it is grounded in reality. The major limitation of using observed records is their relative brevity and sparsity, which can lead to large uncertainties when estimating an extreme event, especially if the desired return period of the estimated event exceeds the length of the observed record. Short observed records of several decades may lead to a systematic underestimation of extreme events¹⁷, which may make unprecedented weather appear impossible using extreme value statistics¹⁸. Other limitations include the susceptibility to measurement errors¹⁹, data inhomogeneities, spatial aggregation (local observation points may not be representative of large events), the dependence on the choice of distribution, sensitivity to the tails of the distribution, the assumption of independent events, and that these methods are limited by what was plausible in a past climate given that they are based on what has happened in the past. In the future, climate events may become more extreme because the mechanisms behind them may change, leading to a different distribution altogether.

Spatially pooling observation stations is one option to increase the observational sample size^{20,21}, noting this may introduce other complexities such as dependence between the observation stations. More

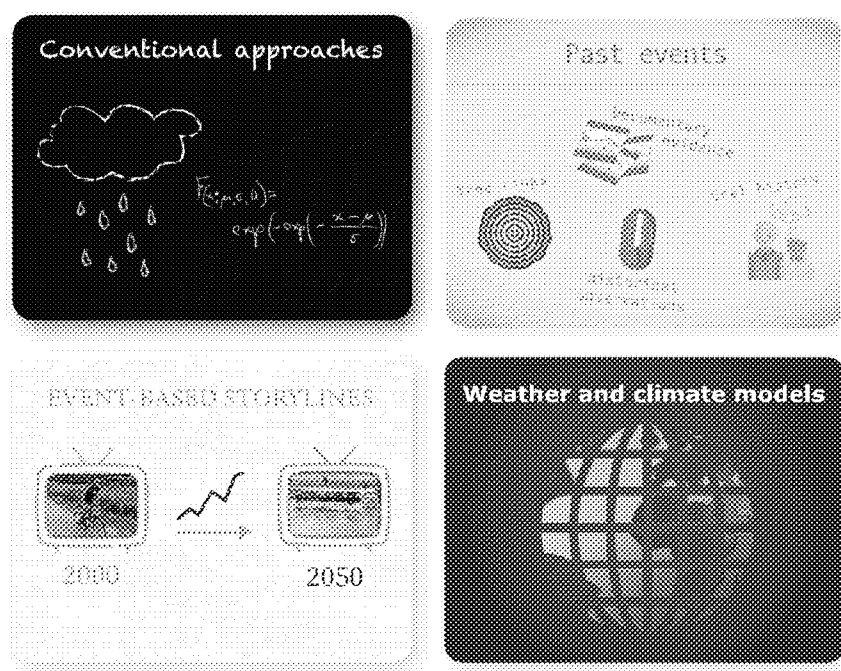


Fig. 1 | An overview of the categories of approaches that exist to identify unprecedented weather. The thermometer icon was made by justicon; tree rings and oral history icons made by Freepik and flood icon made by Konkapp and obtained from www.flaticon.com.

Table 1 | An overview of the four lines of evidence to identify unprecedented weather hazards discussed here, and their key benefits and limitations

Lines of evidence	Benefit	Limitation
Conventional statistical methods using observations	Represent events that actually occurred	Are inherently limited in identifying unseen events
Past events from historical observations, documentary evidence, oral history and proxy data	Help understand events that may have happened before the modern observational records	Are rare, may be challenging to compare to present conditions, and (for the proxy data) have limited resolution
Event-based storylines	Provide a physically plausible unfolding of a single event	Only applies to the single event
Weather and climate-model data exploration	Produce information outside what is possible from observations	Rely on the realism of these models

sophisticated approaches include spatial statistical models based on extreme value theory^{22,23}. A ‘near-miss’ event is sometimes used as a simple observation-based alternative from a nearby station to assess the potential impacts of a historical event that might plausibly occur in a target location. For example, De Bruijn et al.²⁴ studied the potential impacts of the heavy central European rainfall event in 2021 if it had been located over different regions in The Netherlands with different hydrological response characteristics to the affected region. However, such approaches need to make assumptions about whether the same events are plausible at other spatial locations, which is particularly challenging in complex topography, along complex coastlines or heterogeneous land use conditions.

Weather generators are another widely adopted method to increase the sample size by statistically emulating weather events^{12,25–29}. Weather generators also fit a chosen distribution to the historical data. The main difference with extreme values statistics is that while extreme value theory targets just the tails (extremes) of the distribution, weather generators are trained on the entire distribution of events. The strengths of weather generators for estimating extreme weather events include the ability to produce much longer sequences of data than observations; to reproduce temporal/spatial correlation structures²⁸; to incorporate different covariates (such as large-scale atmospheric conditions²⁷) to condition the distribution on a subset of events³⁰; and to incorporate multi-variate dependency and assess compound extremes²⁶. The main challenge for weather generators is producing plausible statistical properties of observed extremes and capturing their interactions given the limited length of observed records. Statistical weather generator accounting based on atmospheric circulation analogues has recently been extensively used to estimate the potential intensity of very rare heat and cold waves³¹.

AI and machine learning models can also support efforts in anticipating and modelling high-impact and unprecedented weather. One of the main current uses of AI models is in weather forecasting, where they have the potential to achieve better performance, longer lead skills and run at much faster speeds than traditional physics-based models. For example, AI-based forecasting models have been shown to outperform traditional numerical models in some metrics, potentially improving early warning systems and disaster preparedness^{32,33}. However, there are other examples where physics-based models still perform better for an extreme event³⁴ and it remains unclear how skilful these methods are in extrapolating to unprecedented events outside their training datasets. One challenge with these approaches is identifying the drivers of unprecedented weather events, noting that advances in explainable AI may offer promising avenues to address this challenge³⁵.

Past events: historical observations, reanalyses, documentary evidence, oral history and proxy data

The ‘modern’ era of observations (after about 1950) is the best sampled period available and includes the recent decades of the most rapid global warming. However, this ~70-year period is short when analysing

unprecedented weather. This section describes approaches to estimating and understanding historical events before this modern era of observations. Longer records can help understand weather events that otherwise would be deemed unprecedented^{36–38}. It can be challenging, however, to directly compare past weather to present conditions, for example, due to changes in land use and infrastructure affecting the impacts of the events, or because of the larger uncertainty which could lead to an over-representation of apparent weather events in the distant past that exceed modern records.

Although *direct instrumental observations* of past weather events that would be unprecedented in the modern era are rare, they are immensely valuable as they represent events that actually occurred. Two striking examples are shown in Fig. 2.

Figure 2a shows the mean temperature for June in Durham, in north-east England, back to 1795^{39,40}. Although June 2023 became Durham’s hottest June since 1940, it is clear that there have been significantly hotter Junes in the past, notably those in 1826 and 1846. Even making careful allowance for uncertainty in temperature records before the modern era⁴¹, the two historical events indicate that monthly mean temperatures at least 1 °C hotter than temperatures recorded in June 2023 have occurred outside the period of modern climate records. Had the same temperatures of June 1846 occurred in June 2023 without the availability of the pre-1850 records, it may have been labelled a record-breaking (or even record-shattering) event, but the longer records enable us to show the full context.

Figure 2b shows the wettest month in each calendar year at Oxford’s Radcliffe Observatory site since 1767⁴². Recently, September 2024 became Oxford’s wettest month in over 200 years with 193.3 mm – such an extraordinarily anomalous month would, for almost anywhere else in the world, appear to be a record-breaking event, but it is still not quite the greatest monthly fall at this very long-period site. In this continuing 250+ year record⁴², September 1774 remains by far the wettest month on record, with around 15% more rainfall than any other month. Although the 1774 rainfall amount appears to be implausible at first sight (particularly since September is rarely the wettest month in any given year), it is well-supported by other independent rainfall measurements and contemporary diaries, together with well-documented severe flooding throughout the river Thames and other catchments. Although the gap between Oxford’s ‘wettest-ever’ and ‘second-wettest-ever’ months has reduced very slightly, when it comes to planning water resource management it is still helpful to be able to indicate – based on clear observational evidence – that a month could still be at least 15% wetter than any experienced in recent times.

Large numbers of existing historical records are yet to be digitised, including meteorological and phenological observations, data from tide gauges, and river flow measurements. The ‘rescue’ of such data from paper or magnetic tape archives can provide valuable information about past events⁴³. For example, in the UK, the driest year on record was recently revised downwards because a lower total rainfall year (1855) was identified through recovering additional and longer observational records by volunteer citizen scientists⁴⁴.

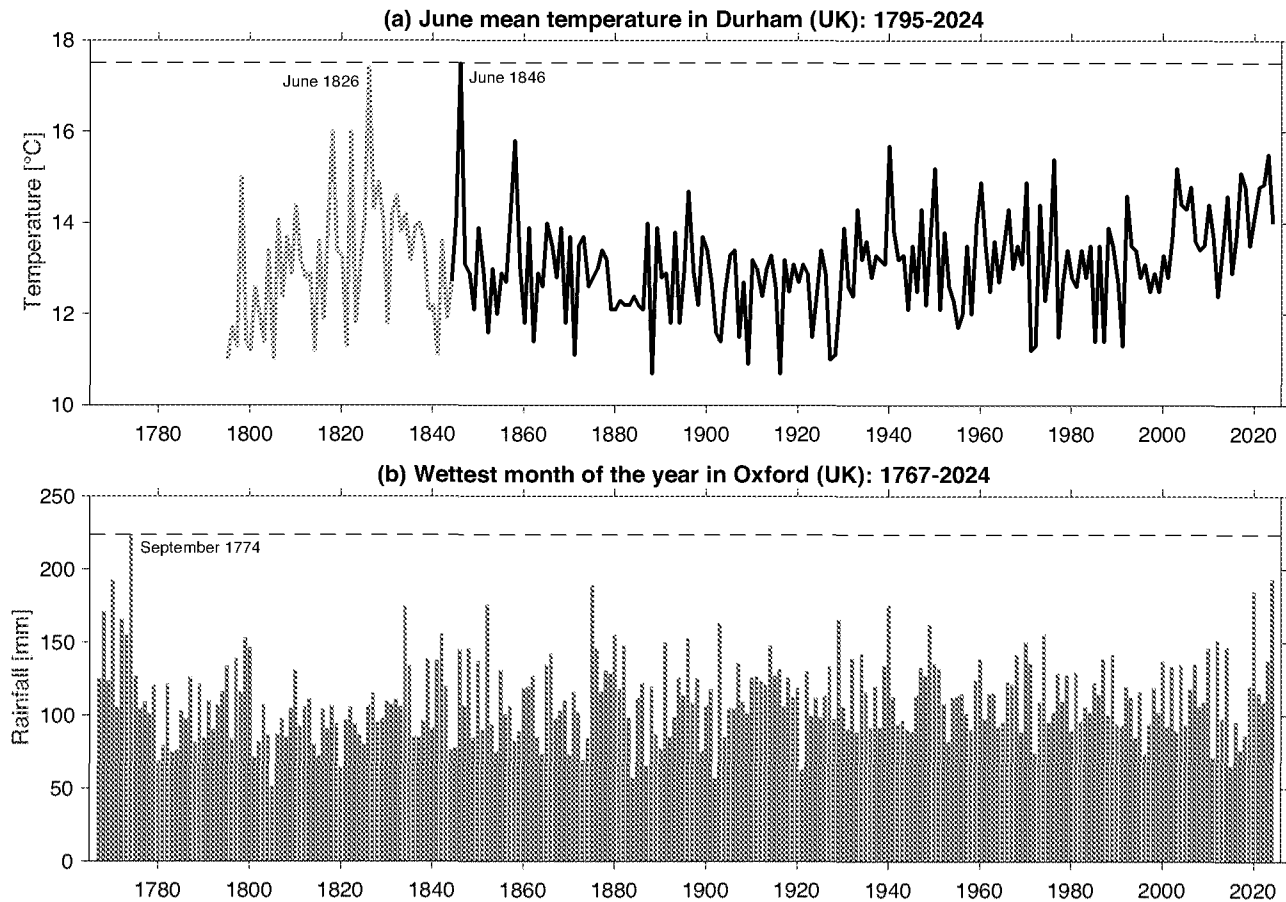


Fig. 2 | Examples of historical weather events which are unsurpassed. In Durham (UK), the two warmest Junes on record occurred in 1826 and 1846, and are $>1.5^{\circ}\text{C}$ warmer than any other June in the post-1850 period (a). The grey lines indicate times when only monthly data are available, whereas daily data are available for the

period shown by the black line. For Oxford (UK), the wettest month on record remains September 1774, around 15% wetter than any other month (b); recently, September 2024 became the second-wettest on the 250+ year record.

Observations are also used to help build *reanalyses* of past weather conditions. These exist for the modern period^{45,46}, on centennial timescales⁴⁷ and even multi-centennial timescales⁴⁸. These datasets blend observations with weather forecast models to produce spatially and temporally coherent outputs, i.e., ‘maps without gaps’⁴⁵ which can be used to consider extreme events and how they are changing. For example, rainfall intensity-duration-frequency (IDF) curves have been estimated globally⁴⁹, and past extreme events have been credibly reconstructed, e.g., a blizzard in 1888⁵⁰ and an intense windstorm in 1903⁵¹. However, they are limited by the availability of observations to constrain the atmospheric circulation, which become more sparse further back in time.

Documentary evidence for past events, in the form of written observational records, photographs, or drawings, can also provide context and show that recent events are sometimes not as unprecedented as they may first appear. For example, the river Ahr (a tributary of the Rhine in Germany), which experienced severe flooding in 2021, also saw extreme floods in 1910 and 1804⁵².

Oral history of past events is another source rooted in local and Indigenous knowledge⁵³, offering another perspective than can be obtained from data^{54–56}, providing a memory which may not exist in observational records. Oral traditions, often shared across generations, provide unique insights into past experiences of extreme weather, highlighting ethical perspectives and cultural values⁵⁷ that are deeply intertwined with environmental knowledge⁵⁸. Beyond identifying unprecedented weather through local forecast knowledge⁵⁹, these narratives convey how people have learned to

cope with extreme weather^{60–62}. In the context of building resilience to unprecedented weather, oral history thus does not only offer past experiences but also embodies place-based wisdom for culturally appropriate responses^{63,64}.

Proxy-based methods can sample rare extreme weather events that may have occurred prior to (and hence are unprecedented in) the modern instrumental data record by reconstructing information from ice cores, coral reefs, speleothems, pollen, ocean sediments, tree rings, and diatoms^{65–69}. Limitations of proxy-based methods are the dating uncertainty; the coarse spatial-temporal resolution relative to direct observations (e.g., decades, centuries or longer); methods are calibrated for the bulk of the distribution and not intended to capture the tails; sensitivity to other signals; degradation of the proxy record’s information content; and the inhomogeneous coverage of reconstructions of extremes⁷⁰. These methods are therefore well-suited for large-scale and long-duration event types, such as droughts^{66,71}, seasonal temperatures over large domains^{68,72} and also certain large floods^{73,74}. Novel approaches also include daily to hourly resolution biogeochemical proxy records⁷⁵, but limitations are substantial and cannot be easily overcome on these timescales. There are also multi-millennial reanalyses which combine climate-model simulations and proxy information to produce global estimates of climatic changes⁷⁶.

Event-based storylines as an alternative to probabilistic approaches

Storylines consist of physically plausible and self-consistent unfolding of climatic events, typically based on historical (high-impact) events.

Storylines focus on plausibility and understanding of the driving factors instead of the occurring probability of such events^{77–79}. This enables the exploration of alternative realisations of the historical event (also known as counterfactuals) through documented changes in the driving conditions, which can include climate change and climate variability information. Examples of the use of storylines to investigate unprecedented weather and its impacts across different fields include floods⁸⁰, tropical cyclones^{81,82}, storms⁸³, crop failures⁸⁴, droughts^{85–87}, among others.

Pseudo Global Warming (PGW) and nudging approaches simulate historical or recent events under alternative scenarios, such as past, present or future climates. Although extreme events are unique and unlikely to reoccur in exactly the same way, this method provides a powerful communication tool, allowing plausible future events to be linked to lived experiences. One common approach uses high-resolution regional climate-model simulations: one of the events in the current climate using reanalysis as boundary and initial conditions, and future and/or past simulations of the event where a mean change signal is added to the boundary and initial conditions^{88–90}. Some studies adapt the method to allow for future changes in large dynamics beyond a mean change^{91,92}. Another technique takes a weather forecast model and reruns with the ocean temperatures and CO₂ concentrations altered to create past and future counterfactuals^{93,94}. Nudging of the atmospheric circulation to impose the dynamical conditions of a specific event can also be applied, for example through large spectral nudging allowing only large-scale features to be constrained^{95–97}. A related approach uses two reanalyses, assimilating the same surface pressure observations and only differing by the SST boundary conditions, to translate specific events into different climates⁹⁸. In these approaches, the structure of the atmosphere is altered – perhaps away from the unique event being assessed. These differences may lead to changes in, e.g., rainfall, thus care must be taken in interpreting results. The development of similar methods by different research groups presents an opportunity to compare results and better understand the limitations and advantages of each. To ensure storylines are relevant for society, the selection of events, the scope of the storylines, and the changes in boundary conditions can be informed by stakeholders' input and/or through investigation of historical high-impact events, including their drivers and sectoral impacts⁹⁹.

Ensemble boosting is another method that may provide input for physical climate storylines^{100,101}. Ensemble boosting uses targeted re-initialisation of very extreme events in large ensembles of fully coupled climate models. Thereby, large ensembles of extreme events in the climate-model can be produced in order to efficiently sample the most extreme events. Ensemble boosting has been applied to quantify and understand potential future multi-year droughts¹⁰², heavy-precipitation events¹⁰³ or very cold winters¹⁰⁴. Additional challenges arise for small-scale events that have shorter predictability timescales and require kilometre-scale models, and the suitability of the ensemble boosting for such types of events requires further testing.

Storylines have the benefit of providing locally relevant information that can directly be integrated into decision-making^{77,79,99}. In addition, storylines improve people's risk awareness, as people react more directly to memorable events than to a range of future possibilities represented by probabilities^{78,105,106}. Limitations include the potential that storylines may not be accepted when produced without local involvement, may miss other plausible unprecedented weather events outside the predefined conditions of the storyline being produced, and that certain decision-making processes, like disaster risk financing mechanisms, require probabilistic information¹⁰⁷.

Weather and climate-model data exploration

The work from Lorenz¹⁰⁸ was pivotal in the suite of approaches for simulating unprecedented weather based on weather and climate-model simulations. Lorenz explained the limitations of weather

predictions induced by the chaotic nature of the atmosphere. By making very small changes in the initial conditions of weather simulations, akin to a butterfly effect, a range of possible weather outcomes is obtained, representing different plausible evolutions of future weather. This presents an opportunity to explore a realistic plausibility range for future weather events^{109,110}. With recent computational advancements and open-source programming¹¹¹, along with the increased attention to high-impact events that occur around the world, this field of science has grown rapidly.

This category of approaches for estimating unprecedented weather gathers the outputs of multiple weather or climate-model simulations to produce a large sample size, relative to historical observations. The difference with previously mentioned weather generators is that these model simulations are based on fundamental principles of physics to simulate numerically the interactions between the atmosphere, ocean, land, and ice, and thus preserve physical consistency across variables and across space and time while weather generators rely more on statistical methods to generate possible weather scenarios. The difference with event-based storylines is that here, we discuss analysing existing weather and climate-model data through search and data-mining techniques, as compared to targeted model-based experiments of individual events.

The benefit of this line of evidence is that it may provide information about physically plausible events that lie outside the range of observed events, and the types of processes that could lead to unprecedented weather. The approach hinges on the limitations of weather and climate models to simulate unprecedented weather realistically. Moreover, the application of bias adjustment can help to compensate for errors between modelled and observed baseline climatology, however, it can also lead to the generation of spurious extremes – such as when uplifting precipitation amounts and thereby runoff events to unrealistic levels¹¹² and hamper the physical consistency across variables¹¹³. This section describes the types of models that can be used, their benefits and limitations, and other similar types of model experiments that have been used for studying unprecedented weather.

Operational weather forecasting centres store large archives of past weather forecasts and seasonal or decadal climate predictions which can be exploited to assess events that have been simulated but not yet occurred. Van den Brink et al.¹⁰⁹ was the first to use probabilistic weather predictions to explore plausible unprecedented weather, after which the approach was popularised as the 'UNSEEN' method: the UNprecedented Simulated Extremes using ENsembles^{110,111}. The strengths of this approach can include increased resolution relative to climate models, the inclusion of additional processes, the ongoing forecast evaluation at weather centres, and the positive impact of the initialisation to reproduce observed weather and climate phenomena¹¹⁴. Key limitations include: events in future climates cannot be studied, that generally numerical weather and climate prediction models have systematic biases depending on the forecast lead time, and that these forecasts represent a limited sample of plausible ocean conditions.

Climate-model projection systems are better suited for understanding unprecedented weather under different climate scenarios and due to the fully coupled atmosphere-ocean interactions also sample ocean and sea ice conditions that have not been recently observed¹¹⁵. The most commonly used models for projecting climate change are available through the Coupled Model Intercomparison Project¹¹⁶. There always has been a trade-off between the resolution of the model and the number of ensemble members that can be used to increase the sample size for detecting extremes, because of the large computational power that weather and climate models require. There is also a trade-off between using a large collection of models and the risk of including biased climate projections. A multi-model ensemble introduces the difficulty of disentangling model uncertainties from the

irreducible uncertainty of outcomes that can happen in the real world. To this end, a *Rare Event Algorithm* has been developed to improve the statistics of extreme events for simulations that are not long enough to sample rare events^{117,118}.

High-resolution climate-model experiments have been simulated for global models through the High-Resolution Model Inter-comparison Project^{119,120} and for regional models through the Coordinated Regional Climate Downscaling Experiment CORDEX^{121,122}. CORDEX offers more reliable information compared to other climate-model experiments about some local-scale sub-daily extremes, such as convective precipitation and wind gusts, allowing the study of future hydro-meteorological extremes^{121,123–125}. A limitation of CORDEX is the small sample size, restricting reliable extreme value estimation. At even higher resolution convection-permitting models improve realism in the simulation of local-scale sub-daily extremes¹²⁶ but are hampered by very limited availability of multi-member and multi-model experiments^{127,128}.

Large numbers of ensemble members have been produced in Single Model Initial-condition Large Ensembles experiments (SMILES^{129,130}). These have the key benefit of extensively sampling climate variability in historical simulations and future climate projections. This developing field of science facilitates the analysis of unprecedented weather with large sample sizes and more robust statistics¹³¹, but the resolution of the climate models used might be too coarse to represent all relevant processes and climate extremes. SMILES can be dynamically downscaled with regional climate models to produce high-resolution large ensembles^{123,132–134}. Despite the coarse resolution, they may be useful to robustly estimate changes and study future events, especially those less affected by lack of high resolution like temperature and drought extremes^{85,86,135,136}.

Using multiple lines of evidence

All of these methods have their benefits and limitations: conventional statistical methods using observations represent events that actually occurred but are inherently limited in identifying unseen events; past events from historical observations, documentary evidence, oral history and proxy data are immensely valuable in helping understand events that may have happened before the modern observational records but are rare, may be challenging to compare to present conditions, and (for the proxy data) have limited resolution; event-based storylines provide a physically plausible unfolding of a single event, but only for a single event; and weather and climate-model data explorations produce information outside what is possible from observations but rely on the realism of these models. As such, these methods may present complementary lines of evidence. Box 1 illustrates the use of four complementary approaches to identify plausible unprecedented heat near the city of Eindhoven, the Netherlands.

How to stop being surprised

We can be surprised by unprecedented weather or unprecedented impacts. To stop being surprised by the hazard, the “Approaches for analysing unprecedented weather” section has discussed scientific advances which could be applied to help anticipate unprecedented weather. To stop being surprised by the impacts, in this section we describe disaster management and climate adaptation approaches to build resilience. These approaches can be seen as three types of adaptation: reactive, incremental, and transformative adaptation¹⁴⁰. These types relate to various components of disaster management: reactive adaptation relates to short-term disaster preparedness and response actions; incremental adaptation refers to long-term disaster prevention; while transformative adaptation relates to transformational risk management and goes beyond reactive and incremental adaptation by aiming to reshape and fundamentally alter the systems, structures, and practices to achieve more just and equitable outcomes¹⁴¹.

Identifying the right mix of measures is important for preparing for unprecedented weather. We use the conceptual ‘adaptation pyramid’ to illustrate how the three different types of adaptation, depicted in three layers, may influence our ability to handle unprecedented weather (Fig. 3). The adaptation pyramid symbolises a climate-resilient system and was developed as a visual instrument and method for adaptation policymakers. This pyramid approach was recently adopted by the national Delta Program in the Netherlands for setting local adaptation goals and targets¹⁴².

Here, we use the pyramid as a concept to build resilience to unprecedented weather. The conceptual adaptation pyramid may help stimulate thinking about transformative actions being the foundation to ensure resilience to unprecedented weather in the long term, with residual risks captured through incremental adaptation and reactive adaptation. Yet, as transformative actions take time, reactive adaptation and short-term disaster preparedness and response actions may be equally important for unprecedented weather that may happen in the near future. We should therefore identify the right mix of actions we can take over time. For each of the layers discussed below, we describe the current practices, gaps, and advances related to the approaches described in the “Approaches for analysing unprecedented weather” section (Table 2).

Reactive adaptation and short-term disaster preparedness

One of the most widely used climate services is weather prediction, which operationally informs early warnings and early action to extreme weather events¹⁴³. By doing so, these predictions help to reduce the impacts from weather extremes and prevent them from escalating into disasters.

However, a gap with the current warning systems is that when there is a warning of something out-of-the-ordinary in terms of severity, duration, and/or timing, some may perceive it as impossible and therefore not take proportionate action on the warning received¹⁴⁴. Research has shown that trust in early warning is determined by experience and perception of risk at that particular moment and may be heightened in high-risk periods or seasons to lead to action^{145–148}. For example, during the October 2021 floods in Nepal, anecdotal evidence suggests that the warnings that were issued to the public were also not as effective as they could have been because they were initially treated with disbelief that a flood could happen that late in the year^{4,149}.

Applying the multiple lines of evidence described above to identify unprecedented weather may help to put those forecasts in perspective. This may inform new gradients of severity for early warnings of forecasted unprecedented weather, or the use of special wording (e.g., through analogues of past events). Whilst research on early warning messaging is significant, more efforts may be placed on the alteration of the content of standard early warning messages for unprecedented weather. Efforts in the research and practice communities are being made to centralise the value of local and Indigenous knowledge about weather and climate and find ways to integrate these knowledge systems and “scientific” forecasts^{150–152}. Particularly for extreme weather, it can be critical to increase the reliability, usefulness, and use of weather predictions at different scales.

Disaster managers often make use of tools such as scenario planning and simulations to prepare disaster response to extreme events^{153–155}. Desktop and active simulations are favoured tools for this whereby practitioners are given a disaster scenario to respond to, sometimes in real-time; discussions and learnings are captured along the way, and these help inform necessary changes or tweaks to contingency plans and future response operations¹⁵⁶. A gap with these scenarios is that they are often designed based on experience with past events, and may not reflect risks from unprecedented weather.

Various approaches to identify unprecedented weather can be used in developing the scenarios. For instance, emergency managers

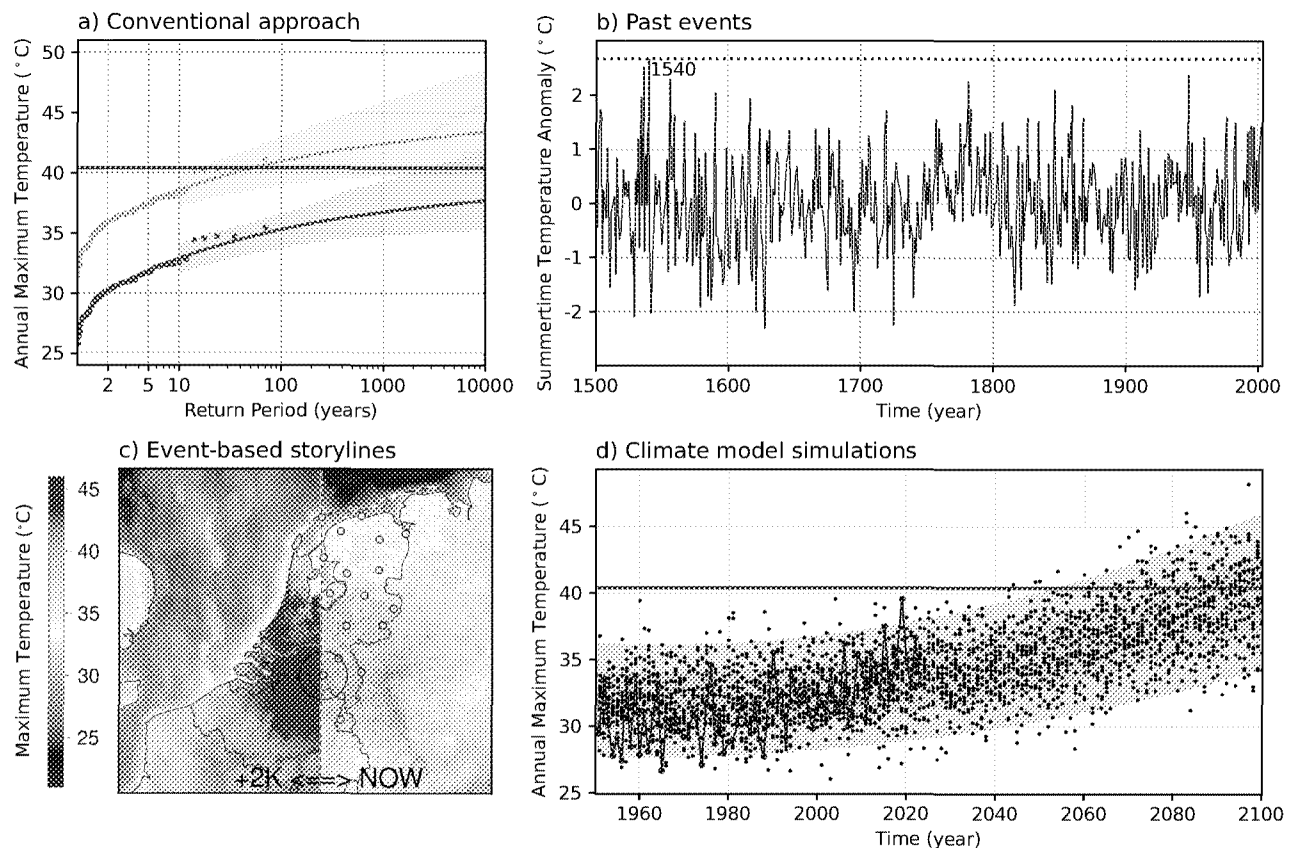
BOX 1

Unprecedented heat in The Netherlands: exploring multiple lines of evidence

Eindhoven is a large city in the south of the Netherlands, situated in the region where on 25 July 2019 the 40 °C-threshold was breached for the first time - the highest recorded temperature in the country since records began. Eindhoven is selected as a case study to illustrate the use of four complementary approaches to identify plausible unprecedented heat in this region (methods described in the Supplementary Materials). The conventional approach shows that there is a large trend in the highest temperatures between the pre-industrial and present climate (Box 1a). Proxy-based methods suggest that the summer of

1540 was most anomalous (Box 1b), supported by previous studies^{68,137–139}. The storyline approach shows that the July 2019 heat-wave would reach up to 45 °C in a 2 °C warmer world (Box 1c). Climate model projections show temperatures of 48 °C near the end of the century under a high-end scenario, noting these are likely underestimates (Box 1d). As such, the methods provide complementary information, together showing strong evidence for the potential of unprecedented heat near Eindhoven beyond that in the conventional observational record.

Extreme Heat in Eindhoven



a Annual daily maximum air temperature at Eindhoven, 1951–2023 (95% CI) with the effects of global mean surface temperature (smoothed) linearly subtracted from the position parameter, for the preindustrial (in green) and current climate (in orange). The observed record temperature of 40.4 °C in 2019, is shown by the red horizontal line (Data is from the KNMI observational network, station number 370). **b** Reconstructed temperature data for summertime (June–July–August) mean temperature anomalies over the Netherlands (3.75–6.75 °E, 51.25–53.75 °N) from 1500 to 2003 (Data taken from KNMI Climate Explorer, as in Luterbacher et al.¹³⁹). **c** Maximum temperature during the three hottest days of the July 2019 heatwave as simulated by the convection permitting climate model HCLIM43 for the current climate (right half) and under +2 K warmer scenario (left half). The small circles in the right half show observations from Dutch Meteorological stations. The large circle is centred around the city of Eindhoven. **d** Annual daily maximum air temperature at the nearest grid point to Eindhoven in ERA5 (blue dots) and in a bias-adjusted 16-member regional climate model ensemble (black dots). The regional climate model RACMO was nested in the global climate model EC-Earth3; historic forcing until 2014, SSP5-8.5 forcing from 2015. Grey shading shows an estimated normal distribution (mean plus 1 and 2 standard deviations) based on the model ensemble.

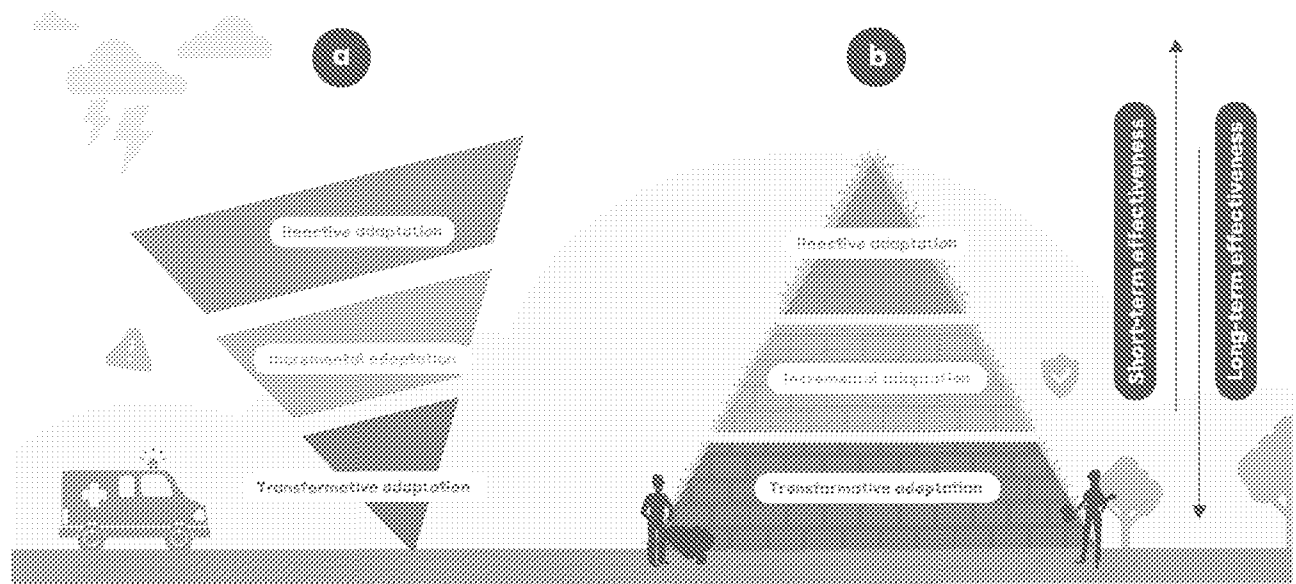


Fig. 3 | The conceptual adaptation pyramid illustrates how three layers of adaptation contribute to resilience to unprecedented weather. a An unstable pyramid: with little transformative actions, we increase our reliance on incremental adaptation and place a lot of emphasis on handling unprecedented weather through early warning, early action and disaster response. **b** A stable pyramid: with more emphasis on transformative actions, we may be able to prevent limits to incremental adaptation, and have to place less emphasis on reactive actions.

Table 2 | A summary of the current practices for each of the layers of adaptation, gaps, and advances related to the approaches described in the “Approaches for analysing unprecedented weather” section, including the discussed case studies

Adaptation layer	Current practice	Gap	Advances	Cases
Reactive	Weather prediction	Limited trust in unprecedented weather forecasts	Putting forecasts of unprecedented weather in perspective	October 2021 Nepal Floods
	Scenario planning	Often designed based on experience with past events	Developing scenarios of unprecedented weather	-
Incremental	Stress testing infrastructure	May under-appreciate the risk of unprecedented weather	Stress-test systems to unprecedented events	UK water security Disruption of food security in the Horn of Africa
	Climate-Resilient Development	Not directly supported by advances in physical climate science	Switches focus from the impacts and hazards towards the underlying development context and drivers of vulnerability	2017 Hurricanes Irma and Maria

can use such scenarios to expand their understanding of plausible unprecedented weather and use this in their planning as well. This information could then be used in contingency plans to respond to these events if/when they occur.

Incremental adaptation

Incremental adaptation maintains the essence and integrity of a system or process at a given scale¹⁵⁷. Incremental adaptation, for example, involves making gradual updates and improvements to existing infrastructure to enhance resilience against climate impacts. Stress testing frequently serves as a method to evaluate how infrastructure can be improved to reduce climate risks to an acceptable level¹⁵⁸. The use of stress testing is most beneficial in highly precautionary circumstances or when critical infrastructure – such as health care, energy and water supplies – could be disrupted. For example, designs for long-lived coastal assets such as ports, flood defences, transport routes, or (nuclear) energy may be stress-tested against a high-end storm, surge, and wave combinations^{83,159,160}.

Climate-model scenarios and conventional statistics are commonly used to calculate these climate risks. However, a gap in using these conventional approaches is that they may under-appreciate the risk of unprecedented weather. The advances in the approaches described in the “Approaches for analysing unprecedented weather”

section may help to stress-test systems to unprecedented weather. For example, in the UK, the resilience of water supply-demand systems has to be assessed for a 1 in 500-year drought. Previously, this has been done using weather generator techniques that can be perturbed to represent climate variability and change. However, large climate-model ensembles can also give likelihoods of problematic conditions for water companies – such as successive dry winters in lowland England^{85,161}. Recent observational data rescue activities have also newly identified a period during the 1850s when UK rainfall was the lowest on record⁴⁴. These unprecedented weather events can also be used to stress-test the efficacy of various strategic water resource options, including water demand management¹⁶².

Storylines can be developed to explore alternative scenarios of unprecedented weather events, such as the effects of concurrent events on the disruption of food security in the Horn of Africa^{99,163}. Using as reference the 2019/21 locust infestation that led to food shortages in that region, counterfactual scenarios are built by combining this event with the multi-breadbasket failures of 2007/08 and the subsequent crop export restrictions that occurred during that same crisis. Results show a considerable increase in impacts, with many countries in the region having food imports reduced by one-third and unable to compensate for the shortages with their own stockpiles. This experiment showcases the potential impacts of

shortages in the region and the need for the global community to secure food aid and support for import-dependent developing countries.

Transformative adaptation

Transformative adaptation goes beyond the gradual adjustments of incremental adaptation by aiming to reshape and fundamentally alter the systems, structures, and practices that shape society's relationship with climate and nature. For example, reshaping and greening cities is not simply a response to climate stressors, but an ambitious rethinking of urban spaces to prioritise resilience, sustainability, and well-being for future generations, when done with equity and justice in focus¹⁴⁰. By definition, transformative adaptation represents a shift in how development practices and policies are carried out, requiring new visions and pathways that change the status quo rather than reinforcing it¹⁴¹.

While reactive or incremental adaptation measures, such as improving flood defences or early warning systems, are directly supported by advances in physical climate science, upcoming practices facilitating transformative adaptation evolve around *Climate-Resilient Development* (CRD). Rather than addressing immediate climate impacts alone, CRD integrates climate adaptation with disaster risk management, climate mitigation, and sustainable development¹⁶⁴. As a result, transformative adaptation switches focus from the impacts and hazards towards the underlying development context and drivers of vulnerability, which avoids exacerbating the conditions¹⁶⁵. For example, the Horn of Africa drought was impactful in part because of the severity and length of the drought, but also because of shortcomings in the current drought management systems³. The most marginalised people, who were already grappling with chronic food and water insecurity, malnutrition, and limited access to basic services, are hit the hardest. More and better designed social protection systems may help decrease poverty and increase resilience to shocks if combined with longer-term visions on moving toward climate-resilient development, which hinges also on reducing greenhouse gas emissions and the achievement of sustainable development.

In the Caribbean, the cases of Hurricanes Irma and Maria in 2017 also demonstrated how existing vulnerability exacerbates the impact of weather events. In Puerto Rico, the hurricanes laid bare the already fragile national grid, affecting everything from homes where diabetes patients kept their insulin refrigerated to hospitals that lost power, forcing physicians to perform surgeries and emergency procedures using mobile phone flashlights¹⁶⁶. The poor state in which the Puerto Rico electric power system met the storms was due to decades of mismanagement of the public energy service corporation combined with a political will to follow privatisation schemes, which proved to make the population even more vulnerable¹⁶⁷. It took up to 6 months for some of the urban settlements to get re-connected, and power outages continue to disrupt both recovery and development. Meanwhile, in Sint Maarten, the remarkable speedy restoration of power to most districts of the 14 sq. mile country within less than a week was a result of the lessons learned from Hurricane Louis in 1995, after which the power company placed electric cables underground – building back better. Despite this progress, a significant portion of low-income residents (approximately 20–25%) still reside in self-organised housing that is highly susceptible to extreme weather and lacks adequate access to electricity and water¹⁶⁸. Although many homes were repaired or rebuilt, those in informal settlements did not receive support¹⁶⁹. A transformation in how support is being provided and to whom is required to reduce future impacts from hurricanes.

Indigenous and local knowledge hold key values in transformative adaptation for climate change^{53,170} and it is key for both researchers and decision-makers to centrally include the memory and perspectives of local and Indigenous communities across their work. As an example, the value of Indigenous knowledge and local

knowledge was evident when looking at the impacts from Irma on water security. The island's large desalination infrastructure was demolished, leaving many without water, and some have argued that traditional practices of decentralised water infrastructure may offer an alternative to incremental engineering practices, enhancing resilience to future hurricanes¹⁷¹.

Transformations include changes to underlying values, world-views, ideologies, structures, and power relationships¹⁶⁴. The transformations may be difficult but can be driven by actions and social choices from multiple actors, from policymakers to civil society, and all sectors, from education, industry, media, science and art. Social cohesion and equity, individual and collective agency, and democratising knowledge processes may drive transformational change¹⁶⁴. Good governance, sustainable finance, and institutional capacity are enabling conditions that contribute to a stable pyramid.

Identifying the right mix of measures

The three layers of options have their benefits and limitations: reactive adaptations are effective in the short term, but may not be enough to ensure future resilience. Incremental adaptation provides very concrete actions to reduce risk from climate change through, e.g., flood defences. However, these may not be as effective when not aligned with a long-term vision and the Sustainable Development Goals (SDGs) and may have negative impacts on marginalised groups (maladaptation). Transformative action is required for future resilience to extreme events and to find efficiencies across various policy domains (SDGs, Sendai Framework, Paris Agreement). However, there is no blueprint for transformative action and because it encompasses such a big topic over a long timescale, it is sometimes critiqued how to go beyond the “blah blah blah” of transformation¹⁷².

Just like the use of multiple lines of evidence in the “Approaches for analysing unprecedented weather” section, the three layers provide complementary actions that together encompass the right mix of measures. For example, the Pacific Northwest heatwave was captured by weather predictions, yet led to over 850 deaths despite early action and disaster response efforts⁵. This event led to questions from some organisations in the Netherlands: could this happen in our city as well?¹⁷³ Multiple lines of evidence point to the potential of unprecedented heat near Eindhoven beyond that in the conventional observational record (Box 1). To stop being surprised by unprecedented heat in the Netherlands, therefore, requires action across the three layers.

Currently, clear heat early actions are limited to yellow and orange warning levels for the national heat action plan in the Netherlands, as these were previously considered the maximum actionable levels for early response. However, discussions have started to rethink the range of possible actions beyond informing organisations that support vulnerable groups, such as introducing small-scale cooling shelters in neighbourhoods when a code red warning is issued¹⁷⁴. Furthermore, disaster managers have started doing the first disaster response exercises for heat¹⁷⁵. The storyline that the July 2019 heatwave could reach up to 45 °C in a 2 °C warmer world was the basis for updating a mindmap from Klok and Kluck¹⁷⁶ of keeping the city liveable in the future, towards keeping the city survivable during unprecedented heat. The mindmap shows that unprecedented heat would put high pressure on critical infrastructure throughout the city simultaneously, with cascading impacts on the city's healthcare (Fig. 4). This mindmap is now being used in the disaster response exercises¹⁷⁵.

However, the discussions around unprecedented heat mostly remain about short-term disaster preparedness and disaster response (the reactive layer). Examples of incremental adaptation in the Netherlands are the stimulation of awnings to prevent buildings from excessive heating, as well as designing urban parks as cool spaces during heatwaves¹⁷⁷. Practitioners may further engage with stress testing of existing infrastructure to unprecedented heat to evaluate if improvements to existing infrastructure are necessary. Furthermore,

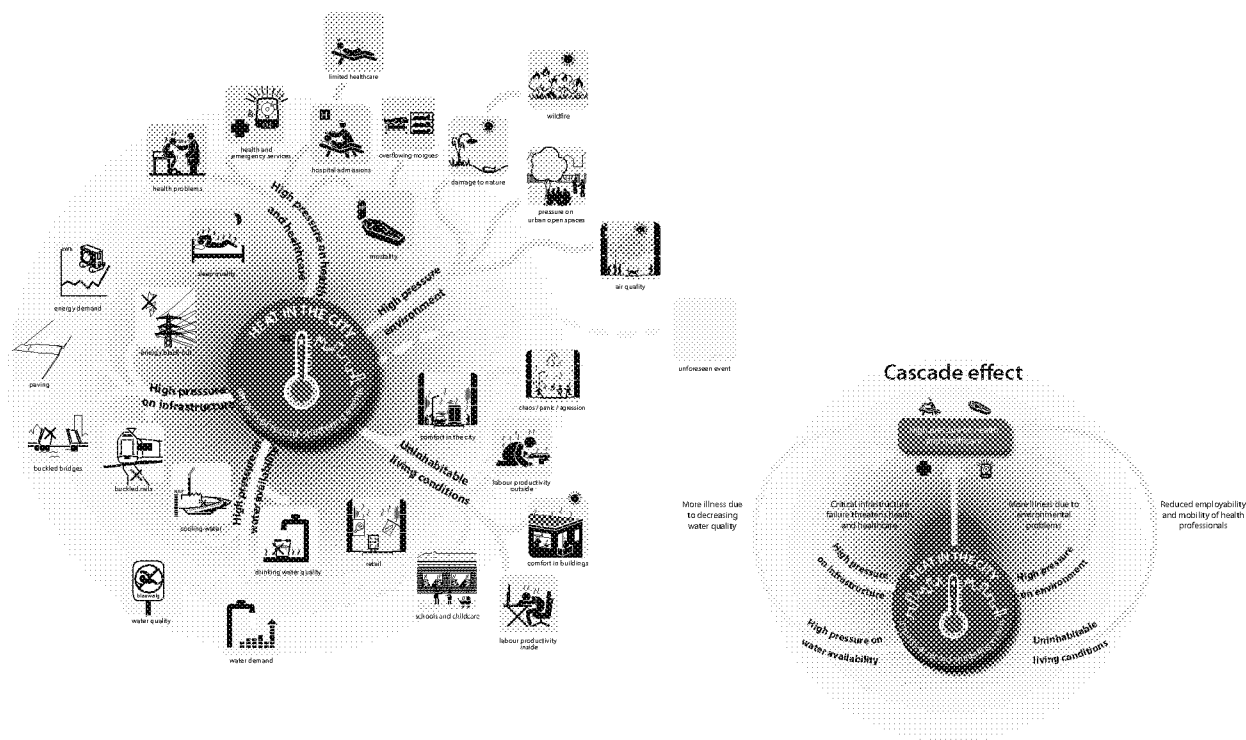


Fig. 4 | Expected impacts and cascading effects of unprecedented heat. This mindmap, based on Klok and Kluck ¹⁷⁶, illustrates how unprecedented heat affects various sectors. On the left, unprecedented heat is positioned centrally, with various colours representing pressures on sectors such as the environment, living

conditions, water availability, infrastructure and healthcare. On the right, the same mindmap is reorganised to illustrate that multiple pressures have cascading impacts on the city's healthcare.

there may be limits to the effectiveness of urban parks and awnings during unprecedented heat. Therefore, practitioners may also stimulate transformational action that moves beyond just tackling heat and may include rethinking the city to prioritise resilience, sustainability, and well-being. Solidarity, social cohesion, and equity are values that help the most vulnerable groups beyond what is possible in early actions during events. Rethinking the healthcare system is an action that relates to almost all of the SDGs, whilst climate mitigation is also crucial to be able to adapt to unprecedented heat.

Conclusion and outlook

We are seeing ‘surprising’ weather happening around the world. The surprise lies in the weather hazard itself or in its (apparent) unexpected impact. There is a growing scientific interest and capabilities in identifying unprecedented weather through various methods, allowing us to stop being surprised by weather hazards. In this paper, we argue that four lines of evidence can provide complementary information to identify plausible examples of unprecedented weather.

In order to stop being surprised by the impacts of these events, building resilience is required at all levels. As a conceptual tool, we use the ‘adaptation pyramid’ consisting of reactive (short-term disaster preparedness and disaster response), incremental (long-term disaster prevention), and transformative adaptation strategies. Each layer plays a distinct role in strengthening resilience: while reactive measures address immediate threats, transformative adaptation builds long-term resilience. A balanced strategy, focusing on both short-term preparedness and structural transformation, is necessary to manage the intensifying impacts from unprecedented weather, with transformative adaptation as the foundation.

The methods for identifying unprecedented weather events enable us to anticipate hazards more accurately, fostering improved reactive and incremental adaptation. Future research may use

principles of co-production at the core for putting the methods to identify unprecedented weather events into action. For instance, the “Exploring Unprecedented Extremes” workshop was convened in November 2023 to guide researchers not only by scientific curiosity but also by the needs of local practitioners and decision-makers¹⁷⁸. The integration of these approaches with Indigenous knowledge and local knowledge will contribute to making solutions locally relevant and culturally appropriate¹⁶⁴. Human and financial capacity, along with the necessary instruments and technologies, are essential to enable the uptake and implementation of the approaches.

Transformative adaptation does not tackle unprecedented weather alone, but centres around adaptive capacity and the drivers of vulnerability through aligning global goals like the SDGs, Sendai Framework, and Paris Agreement. Principles around locally-led adaptation may help the reactive and incremental adaptation actions to stimulate transformational change¹⁷⁹. While climate services support reactive and incremental adaptation, future work may design climate services that support transformational adaptation¹⁸⁰.

Finally, it is key that scientists and policymakers address the enabling conditions and barriers to transformative change and build resilience to unprecedented weather. Key are governance, sustainable finance, and institutional capacity to help various actors build ‘stable pyramids’. This way, we can avoid being surprised by unprecedented weather and ensure that it does not cause unprecedented impacts when it occurs.

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Acknowledgements

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Author contributions

T.K. conceived the study, with L.J.S., R.L.W., E.M.F., K.W., L.S.-G. and H.M.D.G. contributing. T.K. conceptualised the study, with L.K. and D.H. contributing. T.K. drafted the paper with extensive contributions from D.H., L.K., V.T., H.M.D.G., E.H., L.J.S., L.S.-G., R.L.W., E.C.P., E.M.S., S.B.,

B.H., H.V., K.W., E.L.F.S., A.C.B., E.B., and E.M.F. (all authors). E.H. and S.B. produced Fig. 2; V.T., K.W., and H.V. produced Box 1; T.K. and L.K. produced Figs. 1, 3 and 4 with support from colleagues at Climate Adaptation Services Foundation (see “Acknowledgements” section).

Competing interests

The authors declare no competing interests.

Additional information

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From: Judith Curry [curry.judith@gmail.com]
Sent: 5/8/2025 7:58:03 PM
To: Steven Koonin [steven.koonin@gmail.com]
CC: Ross McKittrick [ross.mckittrick@gmail.com]; John Christy [climateman60@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]
Subject: Re: ch 11 managing risks of extreme weather

I think each Part needs a bit of a preamble

On Thu, May 8, 2025 at 12:50 PM Steven Koonin <steven.koonin@gmail.com> wrote:

I don't think we need a separate chapter, but this material would fit in well as the beginning of Part III.

From: Judith Curry <curry.judith@gmail.com>
Sent: Thursday, May 8, 2025 3:44 PM
To: Steven Koonin <steven.koonin@gmail.com>
Cc: Ross McKittrick <ross.mckittrick@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>
Subject: ch 11 managing risks of extreme weather

We don't seem to have a chapter for this? I wrote a small blurb for previous (now defunct) chapter, attached. Do we need such a chapter? If so, I could take a crack at this

On Thu, May 8, 2025 at 11:53 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Will do. I also have to finish going through Chapter 6.

SEK

From: Ross McKittrick <ross.mckittrick@gmail.com>
Sent: Thursday, May 8, 2025 2:27 PM
To: Judith Curry <curry.judith@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Steven Koonin <steven.koonin@gmail.com>
Subject: Ch 7 attribution

Here is a new draft of the attribution chapter. Judy and I did some editing offline for some of the more obscure areas so this version combines our inputs.

I'll post in the Dropbox. Steve maybe you could go through it next.

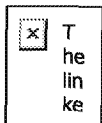
Ross

--



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From: Judith Curry <curry.judith@gmail.com>
Sent: Thursday, May 15, 2025 5:46 PM
To: Travis Fisher
Cc: Ross McKittrick; Roy W. Spencer; John Christy; Steven Koonin
Subject: Re: Ch 2

Thanks travis, i agree with you that we need to tone down the rhetoric on section 2.3

On Thu, May 15, 2025 at 2:18 PM Travis Fisher <travis.scott.fisher@gmail.com> wrote:
Hi all,

I had a few questions about Chapter 2 (in bubbles in the attached document). My goal is to read closely and comment on every chapter before you guys have your marathon walk-through call. Excellent job on this--I didn't realize how strong the effect of CO2 was on crop water productivity.

Best,
Travis



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From: Ross McKittrick [ross.mckittrick@gmail.com]
Sent: 5/17/2025 6:09:02 PM
To: Judith Curry [curry.judith@gmail.com]
CC: Steven Koonin [steven.koonin@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; John Christy [climateman60@gmail.com]
Subject: Re: Ch 3
Attachments: 2 Direct impacts.May17.docx

I inserted them with supporting text in the attached version.

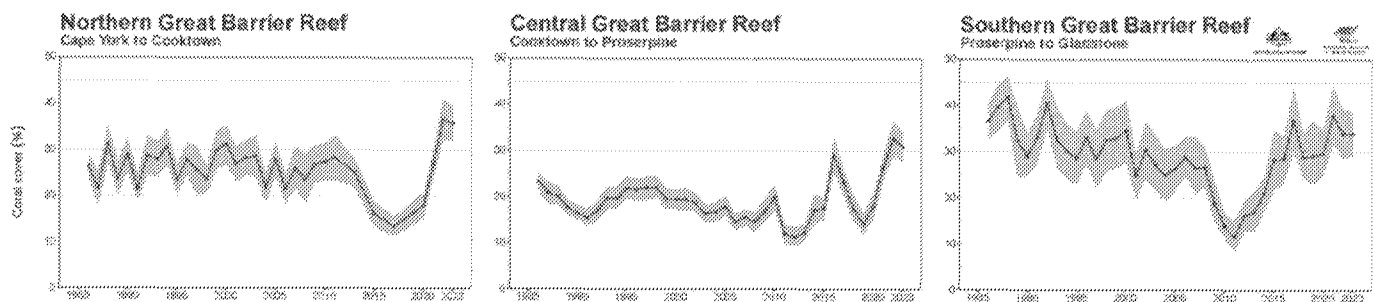
On Sat, May 17, 2025 at 1:50 PM Judith Curry <curry.judith@gmail.com> wrote:
Definitely good to include these graphics

On Sat, May 17, 2025 at 10:11 AM Steven Koonin <steven.koonin@gmail.com> wrote:

You can find an “official” figure on the rebound of the GBR in the AIMS report,
https://www.aims.gov.au/sites/default/files/2023-08/QuickLook_AIMS_LTMP_Report_GBR_coral_status_22_23.pdf

I’ve pasted it below. We should include it in the text, I think.

Amusingly, the report says “The results indicate the recent widespread recovery in the Northern and Central regions of the Great Barrier Reef has paused.” It could have just as well said “Coral levels across the reef are now at least as high as they were forty years ago.”



Regional trends in the percentage of hard coral cover on the Northern, Central and Southern Great Barrier Reef from manta tow surveys by the AIMS Long-Term Monitoring Program up to the 2022/23 survey year.

From: Travis Fisher <travis.scott.fisher@gmail.com>
Sent: Friday, May 16, 2025 11:35 AM
To: Ross McKittrick <ross.mckittrick@gmail.com>
Cc: Steven Koonin <steven.koonin@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; John Christy <climateman60@gmail.com>; Judith Curry <curry.judith@gmail.com>
Subject: Ch 3

I didn't see Chapter 3 in the new "01.Report Draft" folder, so I just added the version that includes my comment bubbles to the folder. I'm also attaching it here for convenience.

Excellent work.

For the rest of the chapters, I'll plan to add comment bubbles directly to the version in the "01.Report Draft" folder.

On Thu, May 15, 2025 at 6:54 PM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

Steve you should write a Figure caption for the chapter explaining that.

On Thu, May 15, 2025 at 6:33 PM Steven Koonin <steven.koonin@gmail.com> wrote:

On Figure 2.2:

I constructed that figure from Figure 3 on pg 192 of this paper: <https://ajsonline.org/article/61570-geocarb-iii-a-revised-model-of-atmospheric-co-2-over-phanerozoic-time>

As you can see from the penultimate paragraph on pg 191 of that paper, "a rough value of 300 ppm" is used to represent the present. So "today" would plot as 1.3 on the graph. In fact, here is the caption from the figure as it appears in "Unsettled"

Figure 3.3 Atmospheric concentration of carbon dioxide

beginning at 550 million years ago. Values determined from the isotopic ratio in carbonate sediments and fossilized soils are relative to the average over the past few million years; today's concentration would be about 1.3 on this scale, down in the lower right-hand corner.⁵

Hope this helps.

SEK

From: Travis Fisher <travis.scott.fisher@gmail.com>

Sent: Thursday, May 15, 2025 5:18 PM

To: Ross McKittrick <ross.mckittrick@gmail.com>

Cc: Roy W. Spencer <roywspencer@hotmail.com>; John Christy <climateman60@gmail.com>; Steven Koonin <steven.koonin@gmail.com>; Judith Curry <curry.judith@gmail.com>

Subject: Ch 2

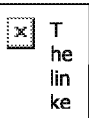
Hi all,

I had a few questions about Chapter 2 (in bubbles in the attached document). My goal is to read closely and comment on every chapter before you guys have your marathon walk-through call. Excellent job on this--I didn't realize how strong the effect of CO2 was on crop water productivity.

Best,
Travis

--

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2 Direct Impacts of CO₂ on the environment

2.1 CO₂ and global greening

The growing CO₂ concentration in the atmosphere has the important positive effect of promoting plant growth by enhancing photosynthesis and improving water use efficiency. That is evident in the “global greening” phenomenon discussed below, as well as in the improving agricultural yields discussed in Chapter 10.

2.1.1 Measurement of global greening

“Greening” refers to an increase in the fraction of the Earth’s surface covered by plants. It can be quantified by the “Leaf Area Index” (LAI) measured by satellite. Many studies over the past decade have confirmed a global greening pattern (increase in LAI) attributable to rising CO₂ levels. Zhu *et al.* (2016) was one of the first studies to report that global greening was detectable using satellite sensors. From 1982 to 2011 they detected greening over 25-50% of the Earth versus “browning” over only 4%, and attributed 70% of the greening to rising CO₂ levels (see Figure 2.1).

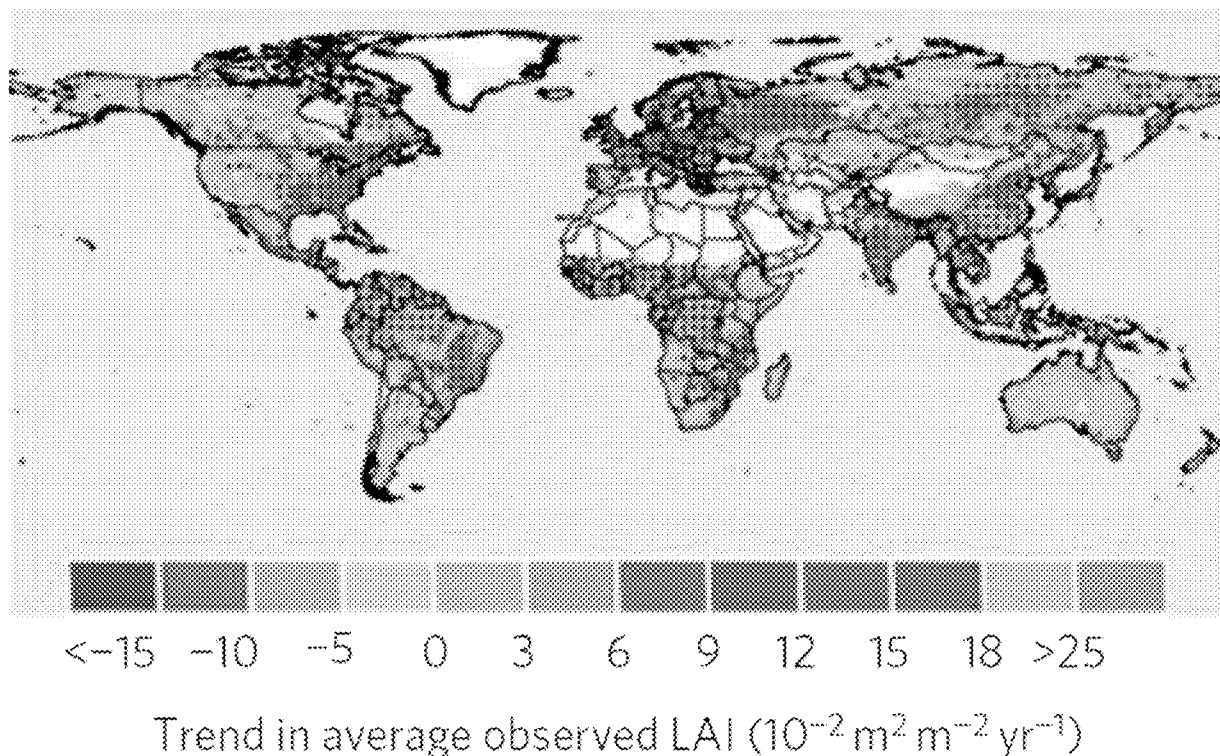


Figure 2.1: Trends in average Leaf Area Index (LAI). Source: Zhu et al. 2016 Figure 3.

Zheng (2017) confirmed the pattern, noting that greening over thirty years had added 8% to global leaf area and that greening was mitigating warming. Greening has been observed globally but Chen et al. (2019) noted that China and India were exploiting it though land management changes. Thus while China accounts for only 6.6% of global vegetated area it accounts for 25% of global net increase in LAI. Piao et al. (2020) noted that greening was even observable in the Arctic.

While plant models predict increases in photosynthesis in response to rising CO₂, Haverd et al. (2020) reported a CO₂ fertilization rate nearly double what models had predicted. That is, CO₂ fertilization had driven an increase in observed global photosynthesis by 30% since 1900, versus 17% predicted by plant models. This indicates that global models of the socioeconomic impacts of rising CO₂ have likely understated the benefits to crops and agriculture. The connection between CO₂ fertilization and climate policy will be discussed in Chapter 10.

Finally, Chen et al. surveyed claims that greening had slowed since 2000 due to drought stress. They found instead that faulty satellite sensors were the cause and that the corrected data showed accelerated greening over 55% of the globe while browning was accelerating over only 7%. In other words, the greening trend continued with no evidence of slowdown, and CO₂ fertilization remained the dominant driver

2.1.2 Photosynthesis and CO₂ levels

Plants build biomass through *photosynthesis*, a process that converts carbon dioxide, water, and light into sugar. The plant enzyme responsible for photosynthesis is called Ribulose-1,5-bisphosphate-carboxylase/oxygenase or “Rubisco”. Photosynthesis is initiated when CO₂ is available at the surface of the RuBisCo enzyme where it is converted to a molecule with 3 carbon atoms and thereafter incorporated into plant mass. This is referred to as the “C3” process.

Rubisco is estimated to have evolved about 3 billion years ago. Over geological time the Earth’s atmospheric CO₂ levels were usually many times higher than they are today, as shown in Figure 2.2

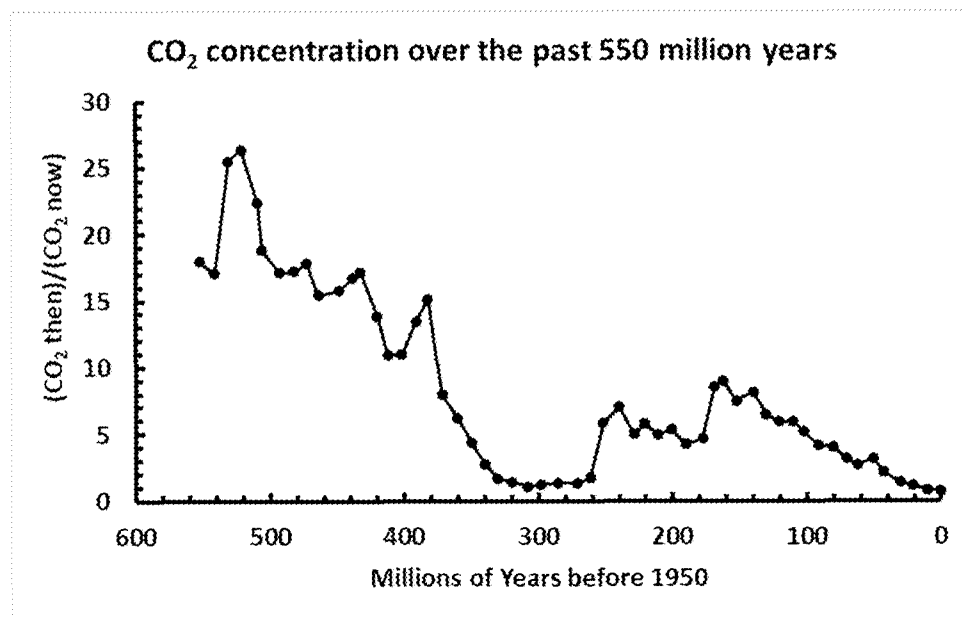


Figure 2.2. Ambient CO₂ levels over the past 550 million years as a multiple of current levels. Source: Adapted from Berner (2006). Current CO₂ levels correspond to about 1.3 times the indicated value at 0.

About 400 million years ago CO₂ levels were an estimated 2,000-4,000 ppm and were at or above 1,000 ppm for much of the interval from 200 to 50 million years ago (Berner 2006, Judd et al. 2024).

Over the past 35 million years the level of atmospheric CO₂ has been steadily declining. During glaciations levels have fallen as low as 170 ppm (Gerhart and Ward 2010).

In response to low-CO₂ conditions some plants evolved another photosynthetic pathway called C4, in which CO₂ is concentrated in the vicinity of Rubisco allowing for the C3 process to function more efficiently. For agricultural purposes the plant categories are:

- C3: rice, wheat, soybeans and most other crops
- C4: maize (corn), sugar cane, millet, sorghum

Had atmospheric CO₂ levels continued declining, plant growth rates would have declined and eventually ceased. Below 180 ppm many C3 species experience growth rate reductions on the order of 40-60% compared to their growth rates at 350 ppm (Gerhart and Ward 2010). C3 plants have been observed under experimental conditions to stop growing altogether at levels between 60—140 ppm CO₂. Some C4 plants are still able to grow at levels even as low as 10 ppm, albeit very slowly (Gerhart and Ward 2010).

Currently, CO₂ levels are about 420 ppm, up from 280 ppm in the early 1800s. The positive response of plants to extra CO₂ is illustrated in Figure 2.3 which is reproduced from Gerhart and Ward (2010). It shows the growth effect of CO₂ on Velvetleaf (*Abutilon theophrasti*) seedlings over 14 days under controlled conditions where only the CO₂ exposure is varied. The gains exhibited from increasing CO₂ from 150 ppm to 350 ppm continue under a further doubling to 700 ppm.

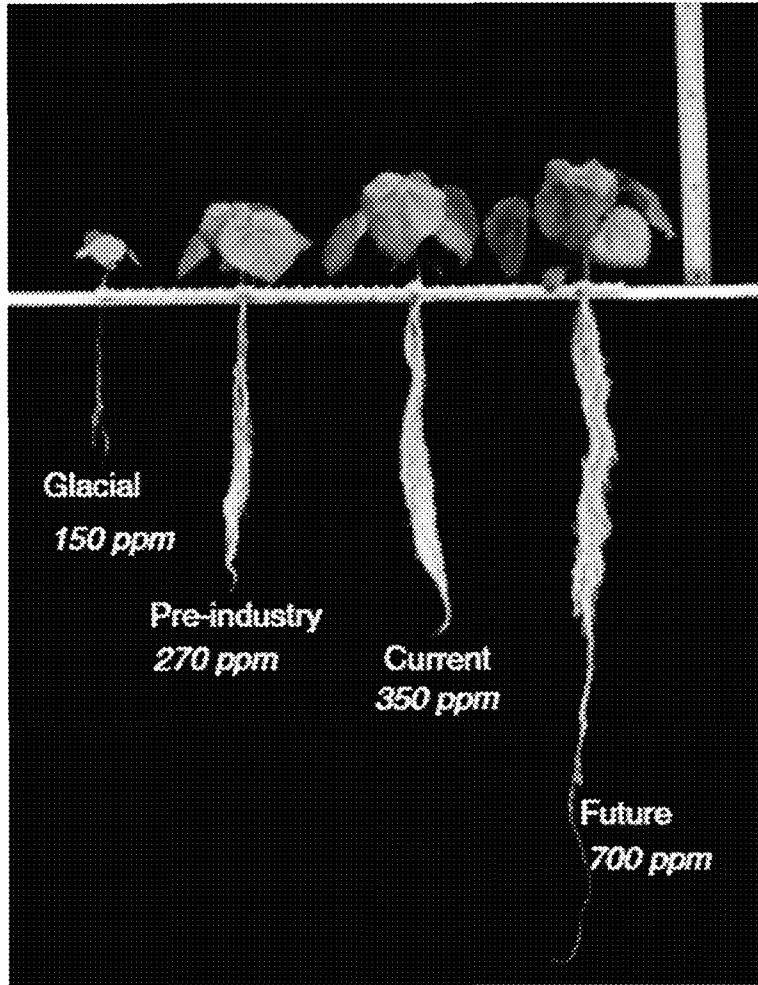


Figure 2.3: growth of *Abutilon theophrasti* after 14 days under identical conditions but for the indicated variations in CO₂ levels. Source: Gerhart and Ward (2010).

Over the past 60+ years there have been thousands of studies on the response of plants to rising CO₂ levels. The overwhelming theme is that plants, especially C3 plants, benefit from extra CO₂. There are two mechanisms by which CO₂ confers a growth benefit:

- Enhanced photosynthesis via the metabolic pathways described above.
- Increased water use efficiency. This arises because plants draw in CO₂ by opening the stomata (pores) on the leaf surface. When CO₂ is scarce the stomata must be kept wide open for long periods, which allows water to evaporate away. Under enriched CO₂ conditions the stomata are closed for longer periods helping the plant retain water longer, thereby increasing water use efficiency.

Specific effects of climate change on US agriculture will be reviewed in Chapter 10.

2.1.3 Rising CO₂ and crop water use efficiency

Deryng et al. (2016) surveyed evidence on crop water productivity (CWP), the yield per unit of water used, drawing attention to the potential for CO₂ both to enhance photosynthesis and reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data (Free Air CO₂ Enrichment—see Chapter 10) on crop yield changes for Maize (corn), Wheat, Rice and Soybean, and combined it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 scenario in four growing regions (Tropics, Arid, Temperate and Cold) each of which were split into rainfed and irrigated sub-regions. In every region they reported that models without CO₂ fertilization predicted CWP losses but CO₂ fertilization more than offset them so that all regions showed a net CWP gain. Deryng et al (2016) also reported that negative impacts of warming on wheat and soybean yields were fully offset by CWP gains and mitigated by up to 90% for rice and 60% for maize.

Similarly, Cheng et al. (2017) noted that increased global plant growth from 1982 to 2011 due to rising CO₂ uptake was accompanied by such large gains in CWP that despite the extra biomass global water use by plants had not increased.

Deryng et al. (2016) assumed that climate change would “exacerbate water scarcity”. It is noteworthy that while models predict drylands will expand under climate warming, current data show the opposite: greening is happening even in arid areas. Zhang et al. (2014) report that due to increased CO₂ levels “increasing aridity in drylands won’t lead to a general loss of vegetation productivity”; increased desertification will happen in at most 4% of currently arid areas.

2.1.4 Concealment of CO₂ fertilization benefits in IPCC Reports

If CO₂ emissions had been discovered to be causing global crop declines and regional browning, that surely would have been discussed prominently in IPCC reports, perhaps even with its own chapter in an Assessment Report if not an IPCC Special Report. By contrast the IPCC has been almost silent on the topic of global greening and CO₂ fertilization of agricultural crops.

The topic is briefly acknowledged in a few places in the body of the IPCC 6th and earlier Assessment Reports but is omitted in all Summary documents. Section 2.3.4.3.3 of the AR6 Working Group I report entitled “global greening and browning” points out that the IPCC Special Report on Climate Change and Land had concluded with *high confidence* that greening had increased globally over the past 2-3 decades. It then discusses that there are variations in the greening trend among data sets, concluding that while they have *high confidence* greening has occurred, they have *low confidence* in the magnitude of the trend. There are also brief mentions of CO₂ fertilization effects and improvements in water use efficiency in a few other chapters in the AR6 Working Groups I and II Reports.

Overall, however, the Policymaker Summaries, Technical Summaries and Synthesis Reports conspicuously fail to discuss the topic.

2.2 Ocean Alkalinity

2.2.1 Changing pH

A neutral aqueous solution has a pH of 7.0, while one with pH greater than 7.0 is basic and with pH less than 7.0 is acidic. The modern-day global average pH of sea water is estimated to be 8.04 (Copernicus Marine Service 2025), down from an estimated value of 8.2 in pre-Industrial times (Gattuso and Hansson, 2011). As CO₂ concentrations in the atmosphere increase, more is absorbed

by the oceans, which decreases alkalinity. Depending upon the buffering capacity of the oceans, the oceans are expected to become somewhat less alkaline over time, consistent with the observed decrease in pH.

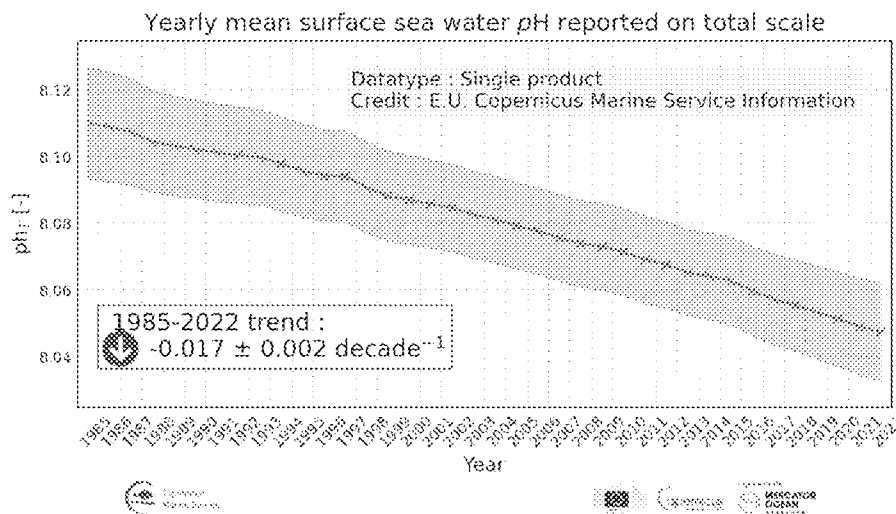


Figure 2.4: Ocean pH 1985 – 2022. Source: Copernicus Marine Service 2025

While this process is often called “ocean acidification”, it is a misnomer because the oceans are not expected to become acidic; “ocean neutralization” would be more accurate. Even if the water were to turn acidic, it is believed that life in the oceans evolved when the oceans were mildly acidic with pH 6.5 - to 7.0 (Krissansen-Totton et al., 2018). On the time scale of thousands of years, boron isotope proxy measurements of pH show that ocean pH was around 7.4 or 7.5 during the last glaciation (up to about 20,000 years ago) increasing to present-day values as the world warmed during deglaciation (Rae et al., 2018). Thus, there appears to be considerable resilience of ocean biota to natural long-term changes in ocean pH since marine organisms are exposed to wide ranges in pH anyway.

2.2.2 Coral reef changes

There are concerns that a decreasing pH of sea water will reduce the calcification rate of coral reefs. But coral reefs already endure large swings in pH, partly due to daily photosynthetic activity in the reef; measured pH values range from 9.4 during the day to 7.5 at night (Revelle and Fairbridge, 1957). De’ath et al. (2009) reported that a portion of Australia’s Great Barrier Reef (GBR, the world’s largest coral reef ecosystem) had experienced a 14% decline in calcification since 1990. This was tentatively attributed to increasing water temperature and decreasing pH. But Ridd et al. (2013) showed that report to have resulted from a biased data analysis which, when corrected, showed no change in calcification rates. Nevertheless, the alarm produced by the original paper has persisted as evidenced by the large number of published citations (541) received by the original study compared to only 11 citations for the correction (as of 30 April 2025).

The most recent annual summary of GBR conditions from the Australian Institute of Marine Science indicates a strong rebound has occurred in coral production (AIMS, 2023). Figure 2.5 shows the results of the AIMS surveys of hard coral cover, expressed as a percentage of the reef area. Much of the decline in the GBR before 2011 turned out to be due to intense tropical cyclone activity (Beeden et al., 2015) as well as a string of marine heatwaves, agricultural runoff and invasive species (Woods

Hole 2023). Given the reported declines in GBR calcification between 1990 and 2009 and the continued increase in atmospheric CO₂ levels the rebound has come as a surprise to some observers.

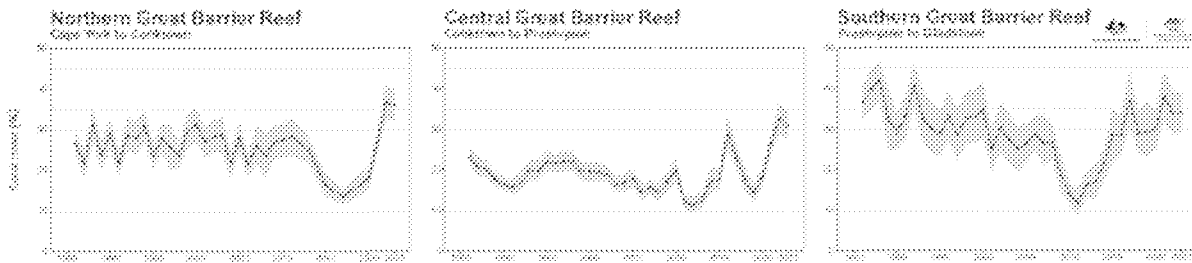


Figure 2.5 Hard coral cover of three regions of the Great Barrier Reef 1985 to 2023. Source: AIMS 2023.

2.2.3 Publication bias

It is being increasingly recognized that publication bias (alarming ocean acidification results preferred by high-impact research publications) exaggerates the impacts of declining ocean pH. An *ICES Journal of Marine Science* Special Issue addressed this problem with an article entitled, *Towards a Broader Perspective on Ocean Acidification Research*. In the Introduction to that Special Issue, H. I. Browman stated, “As is true across all of science, studies that report no effect of ocean acidification are typically more difficult to publish.” (Browman, 2016)

Similarly, a meta-analysis (Clements et al., 2021) of the negative effects of ocean acidification on reef fish behavior found what they called a “decline effect”: initially dramatic conclusions published in prominent journals showing apparently large reported effects of acidification tended to be followed up by subsequent studies on larger sample sizes yielding much smaller and typically non-existent effects. They call for their colleagues to improve research practices to prevent the “decline effect” from persisting:

[The] vast majority of studies with large effect sizes in this field tend to be characterized by low sample sizes, yet are published in high-impact journals and have a disproportionate influence on the field in terms of citations. We contend that ocean acidification has a negligible direct impact on fish behavior, and we advocate for improved approaches to minimize the potential for a decline effect in future avenues of research.

Clements et al. (2022)

In summary, ocean life is complex and much of it evolved when the oceans were acidic relative to the present. Changes to the Australian Great Barrier Reef are driven by many factors other than temperatures or alkalinity and coral cover has recently staged a major rebound. Much of the public discussion of the effects of ocean “acidification” on marine biota has been one-sided and exaggerated. There is a known tendency for studies reporting dramatic effects on things like coral cover and fish behavior to get published in high-impact journals and receive widespread press coverage, then subsequent research rebutting those findings receives little attention.

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From: Judith Curry <curry.judith@gmail.com>
Sent: Saturday, May 17, 2025 1:51 PM
To: Steven Koonin
Cc: Travis Fisher; Ross McKittrick; Roy W. Spencer; John Christy
Subject: Re: Ch 3

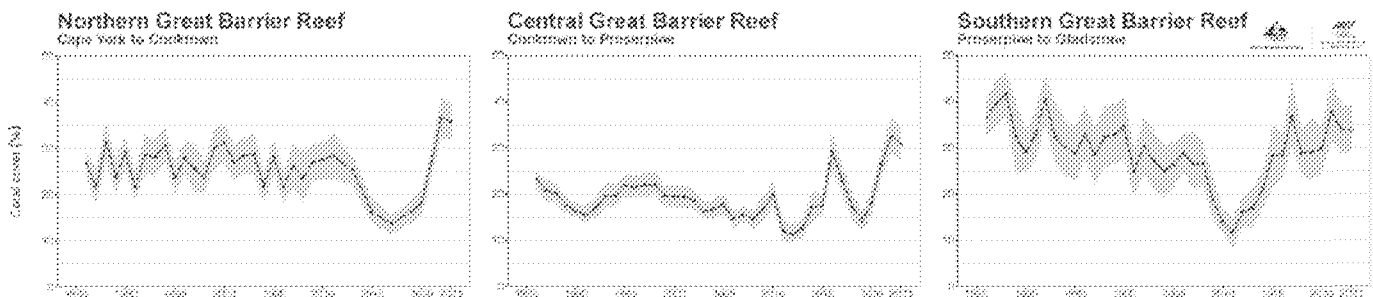
Definitely good to include these graphics

On Sat, May 17, 2025 at 10:11 AM Steven Koonin <steven.koonin@gmail.com> wrote:

You can find an “official” figure on the rebound of the GBR in the AIMS report,
https://www.aims.gov.au/sites/default/files/2023-08/QuickLook_AIMS_LTMP_Report_GBR_coral_status_22_23.pdf

I’ve pasted it below. We should include it in the text, I think.

Amusingly, the report says “The results indicate the recent widespread recovery in the Northern and Central regions of the Great Barrier Reef has paused.” It could have just as well said “Coral levels across the reef are now at least as high as they were forty years ago.”



Regional trends in the percentage of hard coral cover on the Northern, Central and Southern Great Barrier Reef from manta tow surveys by the AIMS Long-Term Monitoring Program up to the 2022/23 survey year.

From: Travis Fisher <travis.scott.fisher@gmail.com>
Sent: Friday, May 16, 2025 11:35 AM
To: Ross McKittrick <ross.mckittrick@gmail.com>
Cc: Steven Koonin <steven.koonin@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; John Christy <climateman60@gmail.com>; Judith Curry <curry.judith@gmail.com>
Subject: Ch 3

I didn't see Chapter 3 in the new "01.Report Draft" folder, so I just added the version that includes my comment bubbles to the folder. I'm also attaching it here for convenience.

Excellent work.

For the rest of the chapters, I'll plan to add comment bubbles directly to the version in the "01.Report Draft" folder.

On Thu, May 15, 2025 at 6:54 PM Ross McKittrick <ross.mckitrick@gmail.com> wrote:

Steve you should write a Figure caption for the chapter explaining that.

On Thu, May 15, 2025 at 6:33 PM Steven Koonin <steven.koonin@gmail.com> wrote:

On Figure 2.2:

I constructed that figure from Figure 3 on pg 192 of this paper: <https://ajsonline.org/article/61570-geocarb-iii-a-revised-model-of-atmospheric-co-2-over-phanerozoic-time>

As you can see from the penultimate paragraph on pg 191 of that paper, "a rough value of 300 ppm" is used to represent the present. So "today" would plot as 1.3 on the graph. In fact, here is the caption from the figure as it appears in "Unsettled"

Figure 3.3 Atmospheric concentration of carbon dioxide

beginning at 550 million years ago. Values determined from the isotopic ratio in carbonate sediments and fossilized soils are relative to the average over the past few million years; today's concentration would be about 1.3 on this scale, down in the lower right-hand corner.⁵

Hope this helps.

SEK

From: Travis Fisher <travis.scott.fisher@gmail.com>

Sent: Thursday, May 15, 2025 5:18 PM

To: Ross McKittrick <ross.mckittrick@gmail.com>

Cc: Roy W. Spencer <roywspencer@hotmail.com>; John Christy <climateman60@gmail.com>; Steven Koonin <steven.koonin@gmail.com>; Judith Curry <curry.judith@gmail.com>

Subject: Ch 2

Hi all,

I had a few questions about Chapter 2 (in bubbles in the attached document). My goal is to read closely and comment on every chapter before you guys have your marathon walk-through call. Excellent job on this--I didn't realize how strong the effect of CO2 was on crop water productivity.

Best,

Travis



Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
<http://www.cfanclimate.net>

From: Judith Curry <curry.judith@gmail.com>
Sent: Sunday, May 11, 2025 9:40 AM
To: Steven Koonin
Subject: Re: Ch 4 Forcing - one point to add.

I'm going through ch 4 again, will send comments later today

On Sun, May 11, 2025 at 6:16 AM Steven Koonin <steven.koonin@gmail.com> wrote:
I'm happy to take lead on Chapter 4.

Judy, what are your issues?
Steven E. Koonin

On May 11, 2025, at 09:13, Judith Curry <curry.judith@gmail.com> wrote:

Who is the lead on ch 4? That is the main chapter I have outstanding issues with (everything else is looking pretty good)

On Sun, May 11, 2025 at 12:08 AM John Christy <climateman60@gmail.com> wrote:
Section 4.1

The other natural forcing component is largely volcanic aerosols, which exert an episodic cooling influence, though there is uncertainty about the sign of the relatively small forcing due to the submarine volcano Hunga Tonga which erupted in 2022 (Jenkins et al. 2023, Schoeberl et al. 2024)

Jenkins, S., Smith, C., Allen, M. et al. Tonga eruption increases chance of temporary surface temperature anomaly above 1.5 °C. Nat. Clim. Chang. 13, 127–129 (2023).
<https://doi.org/10.1038/s41558-022-01568-2>

Schoeberl, M.R., Y. Wang, G. Taha, D.J. Zawada, R. Ueyama and A. Dessler, 2024. Evolution of the climate forcing during the two years after the Hunga Tonga-Hunga Ha'apai eruption. J. Geophys. Res., 129,
<https://doi.org/10.1029/2024JD041296>

John Christy
Director, Earth System Science Center
Professor, Atmos and Earth Science
Alabama State Climatologist
The University of Alabama in Huntsville
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From: Judith Curry [curry.judith@gmail.com]
Sent: 5/11/2025 2:23:31 PM
To: Steven Koonin [steven.koonin@gmail.com]
Subject: Re: Ch 4 Forcing - one point to add.
Attachments: 4.AnthropogenicRF.Apr29 [SEK] JC.docx

my comments on CH 4 are attached

The section on aerosols is 90% attribution and ECS (not forcing). There is much controversy about the aerosol indirect effect, which is barely mentioned.

On Sun, May 11, 2025 at 6:16 AM Steven Koonin <steven.koonin@gmail.com> wrote:
I'm happy to take lead on Chapter 4.

Judy, what are your issues?
Steven E. Koonin

On May 11, 2025, at 09:13, Judith Curry <curry.judith@gmail.com> wrote:

Who is the lead on ch 4? That is the main chapter I have outstanding issues with (everything else is looking pretty good)

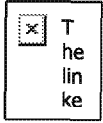
On Sun, May 11, 2025 at 12:08 AM John Christy <climateman60@gmail.com> wrote:
Section 4.1

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Schoeberl, M.R., Y. Wang, G. Taha, D.J. Zawada, R. Ueyama and A. Dessler, 2024. Evolution of the climate forcing during the two years after the Hunga Tonga-Hunga Ha'apai eruption. J. Geophys. Res., 129, <https://doi.org/10.1029/2024JD041296>

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Alabama State Climatologist
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4 Human influences on the climate

4.1 Components of radiative forcing and their history

4.1.1 Historical radiative forcing

A changing climate has been the norm throughout the Earth's 4.6-billion-year history. The Earth's temperature and weather patterns change naturally over timescales ranging from decades to millions of years. Natural variations in the surface climate originate in two ways. Internal climate fluctuations associated with circulations in the atmosphere and ocean produce exchanges of energy, water, and carbon between the atmosphere, oceans, land, and ice. External influences on the climate system include variations in the energy received from the sun and the effects of volcanic eruptions. Human activities influence climate through changing land use and land cover. Humans are also changing the composition of the atmosphere by increasing emissions of CO₂ and other greenhouse gases and by altering the concentrations of aerosol particles in the atmosphere.

The earth is warmed by the sunlight it absorbs and cooled by the radiative heat it emits to outer space. Averaged over Earth, each of these processes involve power flows of about 240 Watts per square meter (W/m²). When they are in balance, there are no net external causes of warming or cooling. ~~Human (and some natural)~~ Both human and natural influences on the climate alter this balance and so cause the climate to change.

Influences on the Earth's energy balance at the top of the atmosphere are quantified by "radiative forcing", the extent to which they disturb the warming/cooling balance; a positive forcing warms while a negative forcing cools. The IPCC's estimated history of major components of radiative forcing since 1750 is shown in the following two figures from the IPCC AR6.

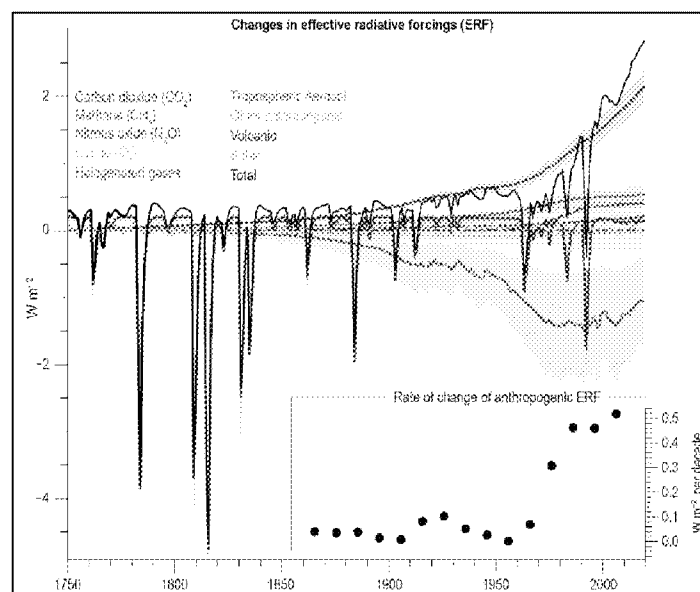


Figure 4.1.1: IPCC estimates of radiative forcing components over time. Source: <https://www.ipcc.ch/report/ar6/wg1/figures/chapter-2/figure-2-10/>

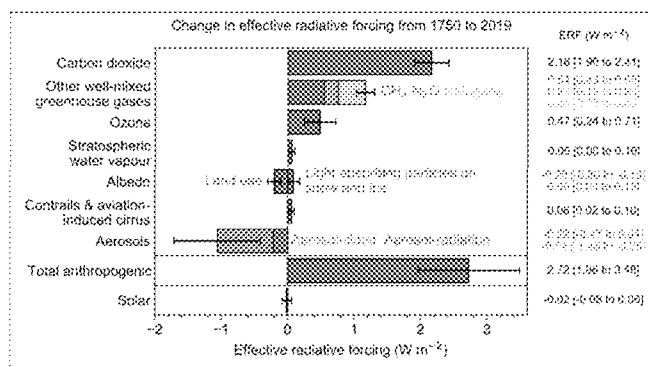


Figure 4.1.2 IPCC estimates of radiative forcing component changes from 1750 to 2019. Source: <https://www.ipcc.ch/report/ar6/wg1/figures/chapter-7/figure-7-6/>

These graphs show that the total radiative forcing is comprised of both natural and anthropogenic components. Carbon dioxide is the largest human influence on the climate and the one most relevant to the effects of energy-using systems like motor vehicles. It exerts a warming influence by decreasing the cooling power of the atmosphere. Emissions of CO₂ are accumulating in the atmosphere, as described in the following section, so that the warming influence is increasing. Other greenhouse gases (methane, nitrous oxide, halogens, and ozone), which act similarly, currently add another 75% to CO₂'s warming. Aerosols exert a cooling effect, although with large uncertainties in the way they catalyze the formation of reflective clouds. As a result, understanding of the causes of recent warming requires not just identifying the warming effects of CO₂, but also the more uncertain cooling effects of sulfate aerosols.

The IPCC views the change in the radiative forcing of the sun to be negligible, based on their preference for reconstructions that imply minimal solar change since preindustrial times. Connolly *et al.* (2021) reviewed sixteen different Total Solar Irradiance (TSI) reconstructions in the literature covering the 1600-2000 interval; they vary from almost no change in TSI to a relatively large upward trend. Connolly *et al.* point out that the variation in TSI reconstructions combined with variations in surface temperature reconstructions implies pairings can be found that are consistent with either no or most 20th century warming being attributable to the sun. A particularly thorny issue is the gap in the TSI data between 1989 and 1991 due to a delay in the launch of a monitor after the Space Shuttle Challenger disaster on January 28 1986, which prevented a replacement satellite from being launched in time to overlap with, and its readings to be intercalibrated with, the prior system (Zacharias 2014, Scafetta et al. 2019). The question of

whether there is an upward trend in TSI over 1978 to 2018 comes down to how the missing data in that gap are filled. That being the case it is noteworthy that Zacharias (2014) observes the solar research community has been motivated by a desire to downplay any potential role of the sun in climate change so as not to detract from arguments for greenhouse gas abatement:

~~A conclusive TSI time series is not only desirable from the perspective of the scientific community, but also when considering the rising interest of the public in questions related to climate change issues, thus preventing climate skeptics from taking advantage of these discrepancies within the TSI community by, e.g., putting forth a presumed solar effect as an excuse for inaction on anthropogenic warming.~~

~~{Zacharias 2014}~~

I'M NOT THRILLED WITH THE ZACHARIAS REF THIS SEEMS LIKE CHEAP POINTS SCORING, AND ATTRIBUTING MOTIVES TO OTHER PEOPLE IS A BAD MOVE. I THINK THE STATEMENT FROM CONNOLLY IS BETTER:

Connolly et al. (2023) found that the Sun/climate debate is an issue where the IPCC's consensus statements were prematurely achieved through the suppression of dissenting scientific opinions.

The other natural radiative forcing component is largely volcanic aerosols, which exert an episodic cooling influence. Box 4.1 in the IPCC AR6 Report addresses the climate impact of volcanic eruptions, noting 3 explosive volcanic eruptions that occurred in the first half of the 19th century. This included the 1815 Tambora eruption that resulted in the 'year without summer', with multiple harvest failures across the Northern Hemisphere.

The anthropogenic forcing component was negligible before about 1900 and has increased steadily since, rising to almost 3 W/m² today. However, this is still only about 1 percent of the unperturbed radiation flows, making it a challenge to isolate the effects of anthropogenic forcing since state-of-the-art satellite estimates of global radiative energy flows are only accurate to a few W/m². Natural sources of global energy imbalance other than volcanoes are not included in these graphs because they remain largely unknown.

4.1.2 Future radiative forcing

Carbon dioxide's warming influence depends upon how much "extra" CO₂ accumulates in the atmosphere- i.e., its concentration. The CO₂ level as recorded at the Mauna Loa observatory in Hawaii is generally used as the representative global average concentration. The data are

available online at <https://gml.noaa.gov/ccgg/trends/index.html>. The concentration was about 316 ppm at the start of the record in 1959 and is now about 425 ppm, a 34 percent increase.

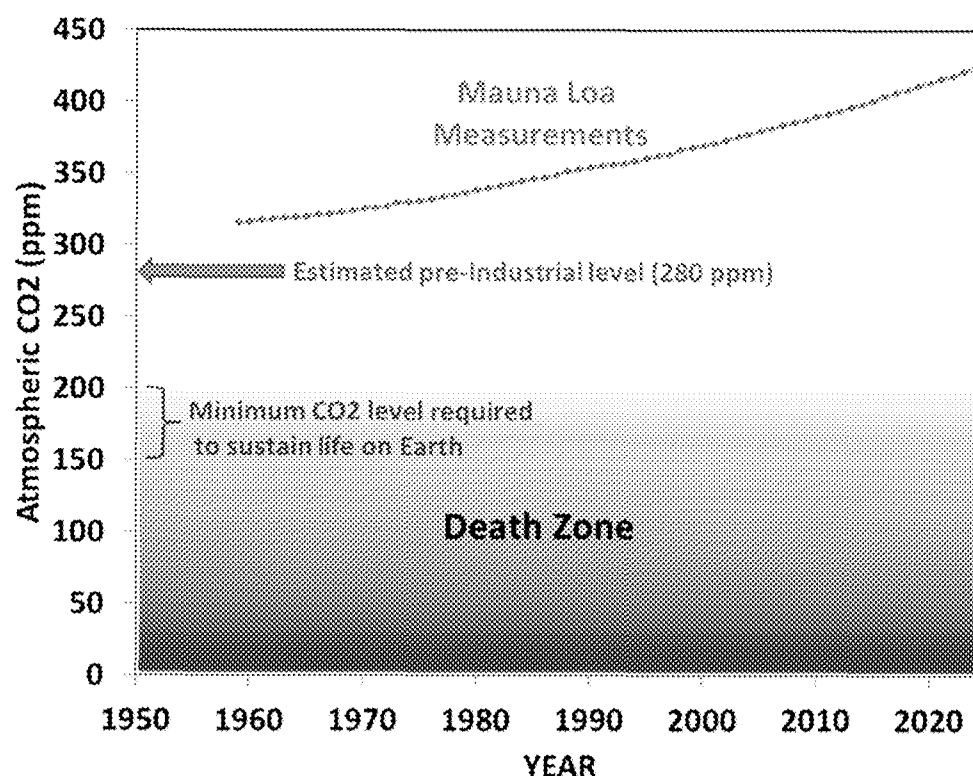


Fig. 4.1.3 Yearly average atmospheric CO₂ concentrations (1959-2024) measured at Mauna Loa, HI (green) compared to the estimated pre-Industrial CO₂ concentration of 280 ppm, and the estimated minimum levels required to sustain life on Earth (150 to 200 ppm). Need source

The annual increase in concentration is only about half of the CO₂ emitted because land and ocean processes absorb “excess” CO₂ at a rate approximately 50% of human emissions. Thus, future concentrations, and hence future human influences on the climate, depend upon two components: (1) future rates of global human CO₂ emissions, and (2) how fast the land and ocean remove extra CO₂ from the atmosphere. We discuss each of these in turn.

4.2 Future emission scenarios and the carbon cycle

4.2.1 Emission scenarios

Assessing the future dangers of GHG emissions requires assumptions about what those emissions will be. Future emissions, and hence human influences on the climate, will depend upon future demographics, economic progress, regulation, and the energy and agricultural technologies in use. Various assumptions about each of those lead to projections of greenhouse gas emissions and concentrations, aerosol concentrations, and changes in land use, which ultimately can be combined into assumptions about anthropogenic radiative forcing.

Because of the great uncertainties about these many factors in the decades to come, instead of making precise predictions of future concentrations, the IPCC has created various sets of scenarios meant to span a plausible range of possibilities for population, economy, technology, and so on. Recent versions of the scenarios are labeled by a number indicating the anthropogenic radiative forcing expected in 2100 under that scenario. Thus, a scenario labeled with a “6” corresponds to 6 W/m² of human-induced radiative forcing (warming) at the end of the century. (Recall current anthropogenic radiative forcing is about 2.7 W/m².)

Although the IPCC does not put its emission scenarios forward as forecasts, they are often treated as such. Comparisons of past scenario groups against observations shows a tendency for IPCC emission projections to overstate actual subsequent emissions. For the IPCC Third and Fourth Assessment Reports a set of emission projections from the *Special Report on Emission Scenarios* were used and hence were referred to as the SRES scenarios. McKittrick *et al.* (2012) showed that, when converted to per capita terms, the SRES scenario distribution was skewed upwards and incompatible with observed trends. McKittrick and Wood (2013) further showed that global energy market dynamics constrained global per capita CO₂ emissions to an extent not reflected in IPCC scenarios. The bias of the SRES scenarios was confirmed by the later analysis in Hausfather *et al.* (2019) who showed that observed atmospheric CO₂ concentrations tracked the low end of the SRES range.

For the Fifth Assessment Report the IPCC developed a new set of scenarios called the Representative Concentration Pathways (RCP). These were identified by a number representing the increase in forcing and were thus called RCP2.6, RCP4.5, RCP6.0 and RCP8.5. RCP2.6 (implying a radiative forcing in 2100 of 2.6 W/m²) projects a GHG concentration pathway leading to warming well below 2 C. At the other end of the scale RCP8.5 is an extreme outcome implying nearly 5 C warming just in this century.

RCP8.5 came to be referred to as the no-policy baseline, or “business-as-usual” scenario in both the academic literature and popular media. It was therefore used to generate the reference outcome supposedly representing the 21st century world in the absence of emission reduction policies. But RCP8.5 was intended as a low-probability high emissions scenario and its usage as a

business-as-usual baseline has been criticized as grossly misleading.¹ Hausfather and Peters (2020) writing in a commentary in *Nature* magazine, pointed out that RCP8.5 was developed as an extreme worst-case, and its misuse as a “business as usual” baseline has resulted in a large number of misleading studies and media reporting: ~~QUOTE NOT NEEDED~~

~~RCP8.5 was intended to explore an unlikely high-risk future. But it has been widely used by some experts, policymakers and the media as something else entirely: as a likely ‘business as usual’ outcome. A sizeable portion of the literature on climate impacts refers to RCP8.5 as business as usual, implying that it is probable in the absence of stringent climate mitigation. The media then often amplifies this message, sometimes without communicating the nuances. This results in further confusion regarding probable emissions outcomes, because many climate researchers are not familiar with the details of these scenarios in the energy modelling literature.~~

~~(Hausfather and Peters 2020)~~

The implausibility of the RCP8.5 scenario was examined by Burgess *et al.* (2021). They noted that RCP8.5 has already diverged from observed energy use trends, and the near future trends diverge sharply from those of the International Energy Agency (IEA) which provides market-based projections of energy use for coming decades. IEA trends are based on plausible extrapolations of current economic and demographic trends, and the results run below the entire envelope of RCP projections, implying not only that RCP8.5 is dubious, but even lower emission scenarios are looking unlikely. ~~Burgess *et al.* comment (p. 8):~~

~~Beyond 2040, if the trends anticipated by energy agency forecasts continue, carbon intensity will continue diverging from AR5 and SSP baselines—especially from higher-emission scenarios such as RCP8.5, due to the assumptions about fossil fuel expansion in these scenarios that are increasingly implausible.~~

Widespread use of RCP8.5 has created an alarmist bias in the climate impacts literature. The extent of this problem was confirmed in a literature analysis by Pielke Jr. and Ritchie (2020). They found ~~(p. 32)~~ that some 16,800 scientific papers published between 2010 and 2020 used the RCP8.5 scenario, with about 4,500 of the articles (p. 16) linking RCP8.5 with the concept of “business-as-usual”. Their analysis showed how RCP8.5 was misused not only by individual researchers, but also by influential science agencies like the IPCC and the US National Climate Assessment (USNCA), which has directly led to misleading coverage in prominent media outlets. ~~They offer the following example (p. 30):~~

¹ This extreme scenario is useful for modelers, since a large forcing generates a large response (warming) making it easier to assess a model’s sensitivity. But that’s very different than claiming it is a plausible future.

~~The USNCA employed RCP8.5 as a baseline scenario, despite warning against such use, and compared it to RCP4.5 throughout its report to generate quantitative economic estimates of the benefits of mitigation. In a front page story, the *New York Times* promoted the report's misuse of RCP8.5 as a baseline scenario:~~

~~"A major scientific report issued by 13 federal agencies on Friday presents the starkest warnings to date of the consequences of climate change for the United States, predicting that if significant steps are not taken to rein in global warming, the damage will knock as much as 10 percent off the size of the American economy by century's end."~~

Pielke and Ritchie (2020) reported new studies using RCP8.5 were appearing in the literature at a rate of about 20 per day, with about two per day specifically linking RCP8.5 and "business as usual." They conclude (p. 34) that the climate research community has spent a decade "committing scientific resources to science fiction" and that "The scientific literature has become imbalanced in an apocalyptic direction." ~~(emphasis added):~~

~~"Derived estimates from RCP8.5 as "business as usual" such as future climate impacts, the impacts avoided from mitigation and the cost effectiveness and benefits of mitigation have no real world meaning... **The scientific literature has become imbalanced in an apocalyptic direction.**~~

~~(Pielke Jr. and Ritchie p. 34)~~

The IPCC developed a new set of scenarios for the AR6, ~~later converted the RCP scenarios to the~~ "Shared Socioeconomic Pathway" or SSP scenarios, but these have continued the pattern of bias shown with the RCP and SRES scenarios. Figure 3.1.4 was generated using the Resources for the Future Global Energy Outlook tool (RFF 2025). The black line shows total global observed CO₂ emissions compiled by the International Energy Agency (IEA). The solid green line is the emission trajectory developed by BP (British Petroleum??) Energy taking account of current emission control policies and global energy use outlooks. It overlaps a solid black line which represents the emission projection from the IEA also taking account of energy use projections and current policies. The dashed lines show the range of IPCC SSP scenarios. As of 2023, global CO₂ emissions have been tracking well below the SSP scenarios especially the two highest ones (SSP5-8.5 and SSP3-7.0).

Carbon dioxide emissions (Million metric tons), by Outlooks & Scenarios. Filtered by Region: World; Fuel: All; Outlook: 2023 Shell (Sky 2050).

Source: RFF Global Energy Outlook at www.rff.org/geo

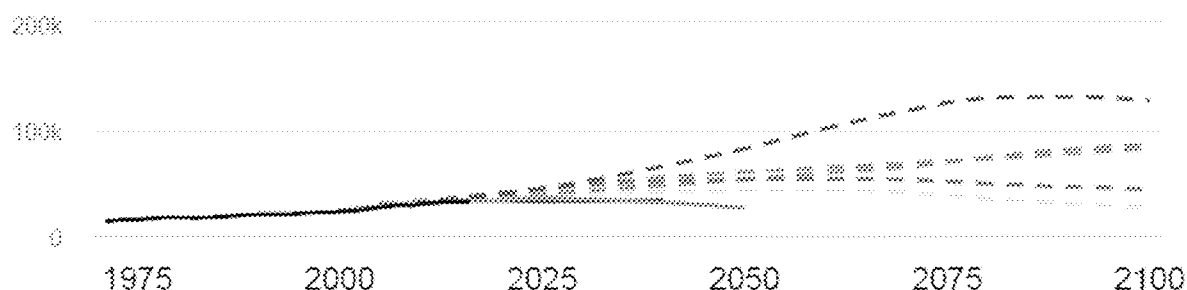


Figure 4.2.1. Observed and projected CO₂ emissions. Source: RFF (2025).

4.2.2 The carbon cycle relating emissions and concentrations

Global carbon cycle models relate concentrations to emissions using estimates of various land and ocean processes that remove CO₂ from, and emit CO₂ into, the atmosphere. Our understanding of these processes was reviewed by Crisp et al. (2021). The natural fluxes of CO₂ in and out of the Earth's surface are very large, many times anthropogenic emissions, but those CO₂ sources and sinks were assumed to be in approximate balance in pre-industrial times, as evidenced by relatively constant levels of atmospheric CO₂ in centuries past derived from air bubbles in ice cores. This is one of several reasons why increasing atmospheric CO₂ levels are believed to be dominated by anthropogenic sources.

Specifically, fossil fuel burning (and to a lesser extent land use [biomass burning] and cement production) has led to steadily increasing CO₂ levels in the atmosphere, as shown in Fig. 1.2.1. CO₂ emissions from fossil fuel burning is a small fraction of the natural carbon cycle components. About 44,000 Gigatonnes of carbon-equivalent (GtC) are stored in the atmosphere and oceans, mostly in the form of CO₂. (Ciais et al. 2013). Between 150 and 200 GtC are released naturally each year through oceanic outgassing and land-based processes like plant decay and animal respiration. A variable but roughly equivalent amount is absorbed each year by the land and oceans, with a small net loss from the atmosphere because the formation of deep ocean sediment sequesters some carbon permanently. Global fossil fuel consumption and cement manufacture released about 10.3 GtC in 2023, up from 6.2 GtC in 1990 (Ritchie et al.

2024). Of this, about half is naturally sequestered through plant growth and oceanic uptake while the remainder, about half, adds to the atmospheric stock (Ciais et al. 2013).

As noted, each year natural processes remove a net amount of CO₂ equivalent to about 50% of global emissions. Thus, anthropogenic CO₂ emissions average twice what is required to explain the atmospheric rise in CO₂ concentration. The near-constancy of that 50% fraction (the “airborne fraction”) also means that the more CO₂ humanity produces, the faster Nature removes it from the atmosphere. That 50% fraction changes somewhat from year to year due to natural carbon cycle imbalances from El Nino, La Nina, and varying weather patterns. There was also a substantial additional reduction in atmospheric CO₂ after the 1991 eruption of Mt. Pinatubo, a curious result that has yet to be explained (Angert et al., 2004).

The main processes which remove excess CO₂ from the atmosphere are increased production of land vegetation (especially at high latitudes), some increase in the sequestering of carbon in soils, and uptake of CO₂ by the ocean due to the increasing partial pressure of atmospheric CO₂ over that of CO₂ dissolved in the ocean. All twenty land carbon cycle models tracked by the Global Carbon Project (Friedlingstein et al., 2024) show land processes have been removing excess CO₂ at an increasing rate since 1959. This is consistent with a “global greening” phenomenon observed by satellites since monitoring of global greenness began in the 1982. This greening has been traced to CO₂ fertilization and greater drought tolerance of plants exposed to elevated CO₂ levels. While there had been some uncertainty whether a greening trend continued beyond 2000, the most recent research (Chen et al., 2023) has shown continued greening, with even some slight acceleration since 2000. Global greening is discussed further in Section 3.1.

While land vegetation has been responding positively to more atmospheric CO₂, uptake of extra CO₂ by ocean biological processes remains too uncertain to be reliably measured. Our current understanding of these and many more carbon cycle processes was reviewed by Crisp et al. (2021).

Public policy can only change the rate of emissions, not the concentration in the atmosphere. For criteria air contaminants the rate and concentration are closely connected because the lifetime is short and the concentration is small. When emissions are reduced the local pollution concentration drops rapidly, usually on a time scale of a few days. Not so with the global average CO₂ concentration since global carbon cycle is vast and slow. A change in local emissions today will only have a very small global effect, and only after a long time lag. After a pulse (release) of CO₂ emissions to the atmosphere only about 40 percent ($\pm 15\%$) of the extra CO₂ will have been sequestered after twenty years. After a thousand years about 75 percent ($\pm 10\%$) will have been sequestered, and the remainder will gradually be removed over the ensuing tens of thousands of years (Ciais et al. 2013, pp. 472-473). Consequently US CO₂ emission reductions will take decades or centuries to lead to a reduction in the global CO₂ concentration.

To reduce the atmospheric stock of CO₂, assuming the entire increase is anthropogenic, would require emissions to fall below the natural sequestration rate. Since that rate has been averaging about 50% of emissions, a reduction of global emissions by 50% would (at least temporarily) halt the rise in atmospheric CO₂. The 1997 Kyoto Protocol proposed to cap industrial nations' CO₂ emissions at a modest five percent below 1990 levels by the year 2012. Even though this policy ended up being too costly for most nations to implement, full compliance would not have substantially reduced atmospheric CO₂ levels. It would only have slightly slowed CO₂ growth, reaching the projected 2100 level in 2105 instead (Wigley 1998). Similarly, Lomborg (2016) used the widely-used MAGICC climate model and showed that full compliance with the Paris Accord would not stop warming, it would only prevent about 0.1C warming and delay hitting the baseline year 2100 temperature levels by about a decade.

Thus, in contrast with conventional air pollution control, local actions yield extremely small local effects, and only after a long time lag. The practice of referring to unilateral US reductions as “combatting climate change” or “taking action on climate” reflects a profound misunderstanding of the scale of the issue. The scale problem is compounded by recognizing that US motor vehicles account only for about 4 percent of global CO₂ emissions so even a fifty percent reduction in those emissions would have a vanishingly small effect on the global climate.

4.3 Aerosols and the uncertainties associated with them

JUST DELETE THIS SECTION. MOST OF THIS IS ECS OR ATTRIBUTION MATERIAL, NOT FORCING

The role of this chapter should be to address radiative forcing – not ECS or warming attribution. I think that the material in this section should be moved to ECS or attribution. There is huge uncertainty in the aerosol indirect effect, which relates directly to radiative forcing. I can write up something on this

THIS PARA SHOULD BE DELETED HERE, THIS IS COVERED IN THE ATTRIBUTION CHAPTER and the Climate sensitivity chapter

~~THIS CAN GO IN ECS CHAPTER Research on the strength of aerosol cooling is therefore central to more precise ECS estimates. Lewis and Curry (2018) note that after the IPCC AR5 was published in 2013, eleven studies appeared in the scientific literature all finding that aerosol cooling was weaker than had previously been conjectured. Combining the updated aerosol estimates with greenhouse gas, ocean heat uptake and atmospheric warming data from the IPCC and applying standard empirical methods, Lewis and Curry (2018) estimated the best-~~

~~guess ECS to be 1.66°C with a 95 percent uncertainty range of 1.15 °C — 2.7°C. They concluded that based on the ECS values derived from most IPCC climate models were incompatible with observed data.~~

There has been further evidence of lower aerosol cooling (implying lower ECS) such as Liu et al. (2021). THIS COULD BE MADE TO BE RELEVANT TO RADIATIVE FORCING CHAPTER These authors tested the hypothesis that aerosols from wildfires has increased since before the 20th century which, if true, would mean there had to have been relatively strong CO₂ warming over that period offsetting the aerosol cooling. They examined soot layers in ice cores extracted from Antarctica and South America and determined that wildfire activity prior to the 20th century was higher than previously believed. Instead of wildfire activity rising steadily from the 1700s to the present, it was high all the time, thus contradicting the hypothesized aerosol cooling trend in the Southern Hemisphere during the 20th century. They pointed out how this finding relates to the climate sensitivity issue:

Accurate estimates of aerosol radiative forcing are also crucial for better understanding the transient climate response (TCR) and equilibrium climate sensitivity (ECS) to increasing CO₂ and more accurate projection of future climate change. The negative aerosol radiative forcing can, in part, cancel out the positive forcing of increasing greenhouse gases and contribute to the uncertainty of total radiative forcing. An overly large aerosol cooling implies that models might overestimate TCR and ECS to reproduce historical temperature response. A recent study using one of the latest-generation CMIP6 climate models (E3SM) suggested that reducing both the magnitudes of negative aerosol radiative forcing and climate sensitivity yields a better agreement with the observed historical record of the surface temperature.

(Liu et al. 2021)

~~Liu told the UK Daily Mail²~~

~~Climate scientists have known that the most recent generation of climate models have been over-estimating surface temperature sensitivity to greenhouse gasses, but we haven't known why or by how much. This research offers a possible explanation.~~

I really think we should limit direct quotes to IPCC or other official docs, or something that is especially profound.

² Available online at <https://www.dailymail.co.uk/sciencetech/article-9629919/Climate-change-warming-effect-greenhouse-gases-overestimated-ice-core-study-suggests.html>

~~THIS IS ATTRIBUTION~~ More evidence pointing to weak aerosol cooling was reported by Wang *et al.* (2021). They noted that the strength of aerosol cooling is partly mediated by cloud behavior and differs between the North and South Hemispheres because of the different density of aerosol emissions. This allowed them to construct another test of climate model validity, which came out in favor of low ECS models. In their words:

Since anthropogenic aerosols primarily concentrate in the Northern Hemisphere, strong aerosol cloud interaction models produce an interhemispheric asymmetric warming. We show that the observed warming asymmetry during the mid to late 20th century is more consistent with low ECS (weak aerosol indirect effect) models. PARAPHRASE, DIRECT QUOTE NOT NEEDED

Wang et al. (2021)

~~THIS PARA IS AN ATTRIBUTION STATEMENT, NOT A FORCING STATEMENT~~ To summarize, quantifying warming due to CO₂ requires understanding the strength of aerosol cooling. While that latter is uncertain a substantial body of recent evidence points to it being relatively weak, implying that CO₂ warming is likewise weak.

Summary

- The global climate is naturally variable. Anthropogenic CO₂ emissions add to that variability by changing the total radiative balance in the atmosphere.
- The IPCC has downplayed the role of the sun in climate change but there are Total Solar Irradiance reconstructions that imply it might have been important, and the modern record is uncertain due to an interruption in satellite coverage.
- ~~Projections of anthropogenic emissions are combined with carbon cycle model estimates of atmospheric CO₂ removal to estimate future CO₂ concentrations and hence the radiative forcings. These are input to climate models to estimate future anthropogenic changes in the climate.~~
- IPCC emission scenarios envelopes have tended to exceed observed trends.
- The vast majority of academic climate “impacts” studies in recent years are based upon the extreme RCP8.5 scenario that is considered implausible; its usage as a business-as-usual scenario is misleading.
- Despite ample evidence that scenario envelopes are exaggerated, and despite criticism of this practice in the peer-reviewed literature, the IPCC’s most recent scenario set (SSP) perpetuates this malpractice.

- The global carbon cycle heavily dampens the effect of changes in local (e.g. U.S.) CO₂ emissions. Even global-scale emission reductions will have only small, much delayed effects.
- ~~Knowing the magnitude of CO₂ warming requires knowing the strength of aerosol cooling. While that is uncertain, a substantial body of recent evidence points to it being relatively weak, implying CO₂ warming is likewise weak. THIS IS AN ATTRIBUTION STATEMENT~~

Scaffeta, Nicola, Richard C. Willson, Jae N. Lee and Dong Wu (2019) Modeling Quiet Solar Luminosity Variability from TSI Satellite Measurements and Proxy Models during 1980–2018. *Remote Sensing* 11(21) 2569 <https://doi.org/10.3390/rs11212569>

Connolly, Roman, Willie Soon, Michael Connolly et al. (2021) How much has the Sun influenced Northern Hemisphere temperature trends? An ongoing debate *Research in Astronomy and Astrophysics* 21(6) doi: 10.1088/1674-4527/21/6/131 <https://iopscience.iop.org/article/10.1088/1674-4527/21/6/131>

Zacharias, Pia (2014) An Independent Review of Existing Total Solar Irradiance Records. *Surveys in Geophysics* 35 pp. 897—912 <https://link.springer.com/article/10.1007/s10712-014-9294-y>

Liu, Pengfei et al. (2021) “Improved estimates of preindustrial biomass burning reduce the magnitude of aerosol climate forcing in the Southern Hemisphere” *Science Advances* 7(22) May 2021 <https://doi.org/10.1126/sciadv.abc1379>

Wang, C., Soden, B. J., Yang, W., & Vecchi, G. A. (2021). Compensation between cloud feedback and aerosol-cloud interaction in CMIP6 models. *Geophysical Research Letters*, 48, e2020GL091024. <https://doi.org/10.1029/2020GL091024>

From: Judith Curry <curry.judith@gmail.com>
Sent: Sunday, May 11, 2025 9:13 AM
To: John Christy
Cc: Ross McKittrick; Steve Koonin; Roy Spencer; Travis Fisher
Subject: Re: Ch 4 Forcing - one point to add.

Who is the lead on ch 4? That is the main chapter I have outstanding issues with (everything else is looking pretty good)

On Sun, May 11, 2025 at 12:08 AM John Christy <climateman60@gmail.com> wrote:
Section 4.1

The other natural forcing component is largely volcanic aerosols, which exert an episodic cooling influence, though there is uncertainty about the sign of the relatively small forcing due to the submarine volcano Hunga Tonga which erupted in 2022 (Jenkins et al. 2023, Schoeberl et al. 2024)

Jenkins, S., Smith, C., Allen, M. et al. Tonga eruption increases chance of temporary surface temperature anomaly above 1.5 °C. Nat. Clim. Chang. 13, 127–129 (2023). <https://doi.org/10.1038/s41558-022-01568-2>

Schoeberl, M.R., Y. Wang, G. Taha, D.J. Zawada, R. Ueyama and A. Dessler, 2024. Evolution of the climate forcing during the two years after the Hunga Tonga-Hunga Ha’apai eruption. J. Geophys. Res., 129, <https://doi.org/10.1029/2024JD041296>

John Christy
Director, Earth System Science Center
Professor, Atmos and Earth Science
Alabama State Climatologist
The University of Alabama in Huntsville
climateman60@gmail.com

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Judith Curry, President
CFAN - Climate Forecast Applications Network
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curry.judith@cfanclimate.com | +1.404.803.2012
<http://www.cfanclimate.net>

From: Ross McKittrick [ross.mckittrick@gmail.com]
Sent: 5/21/2025 2:07:01 PM
To: Judith Curry [curry.judith@gmail.com]
CC: Steve Koonin [steven.koonin@gmail.com]; John Christy [climatemanager60@gmail.com]; Roy Spencer [roywspencer@hotmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]
Subject: Re: ch 4 revisions
Attachments: S02 Hall and Manabe.pdf

Hall and Manabe 1997 (attached, Fig 3) is the one I use to make the point about 1C direct effect from CO2 doubling. Yesterday we were debating the forcing amount from CO2 doubling.

On Wed, May 21, 2025 at 10:03 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:
What is the citation indicated as a superscript 33?

On Wed, May 21, 2025 at 9:31 AM Judith Curry <curry.judith@gmail.com> wrote:
attached, added text in red

--



Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
<http://www.cfanclimate.net>

The Role of Water Vapor Feedback in Unperturbed Climate Variability and Global Warming

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Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

(Manuscript received 6 November 1997, in final form 9 June 1998)

ABSTRACT

To understand the role of water vapor feedback in unperturbed surface temperature variability, a version of the Geophysical Fluid Dynamics Laboratory coupled ocean–atmosphere model is integrated for 1000 yr in two configurations, one with water vapor feedback and one without. For all spatial scales, the model with water vapor feedback has more low-frequency (timescale ≥ 2 yr) surface temperature variability than the one without. Thus water vapor feedback is positive in the context of the model's unperturbed variability. In addition, water vapor feedback is more effective the longer the timescale of the surface temperature anomaly and the larger its spatial scale.

To understand the role of water vapor feedback in global warming, two 500-yr integrations were also performed in which CO_2 was doubled in both model configurations. The final surface global warming in the model with water vapor feedback is 3.38°C , while in the one without it is only 1.05°C . However, the model's water vapor feedback has a larger impact on surface warming in response to a doubling of CO_2 than it does on internally generated, low-frequency, global-mean surface temperature anomalies. Water vapor feedback's strength therefore depends on the type of temperature anomaly it affects. The authors found that the degree to which a surface temperature anomaly penetrates into the troposphere is a critical factor in determining the effectiveness of its associated water vapor feedback. The more the anomaly penetrates, the stronger the feedback. It is also shown that the apparent impact of water vapor feedback is altered by other feedback mechanisms, such as albedo and cloud feedback. The sensitivity of the results to this fact is examined.

Finally, the authors compare the local and global-mean surface temperature time series from both unperturbed variability experiments to the observed record. The experiment without water vapor feedback does not have enough global-scale variability to reproduce the magnitude of the variability in the observed global-mean record, whether or not one removes the warming trend observed over the past century. In contrast, the amount of variability in the experiment with water vapor feedback is comparable to that of the global-mean record, provided the observed warming trend is removed. Thus, the authors are unable to simulate the observed levels of variability without water vapor feedback.

1. Introduction

The precise amount of warming that would take place for a given increase in greenhouse gases in the atmosphere remains an unknown quantity. According to the latest Intergovernmental Panel on Climate Change as-

essment, the likely equilibrium global-mean temperature response to a doubling of CO_2 ranges from 1.5° to 4.5°C (Intergovernmental Panel on Climate Change 1996). The source of this uncertainty is our inability to quantify the role of feedback mechanisms in the climate system, including water vapor, cloud, lapse rate, and albedo feedback. Water vapor feedback, the subject of this study, has long been thought to be a positive feedback mechanism (see, e.g., Manabe and Wetherald 1967). This is due to the dependence of the saturation water vapor mixing ratio on temperature, as predicted by the Clausius–Clapeyron equation. Thus a CO_2 -induced warming of the surface–troposphere system will lead to a water vapor increase in the atmosphere. Since water vapor is itself a greenhouse gas, this increase will reduce the longwave radiative damping of the temper-

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ature anomaly, making the warming larger than it would be otherwise. While there is a consensus that water vapor feedback is positive in the context of global warming, it remains unclear exactly how strong the effect is (Dickinson et al. 1996). Large uncertainties also exist regarding the magnitude (and sign, in the case of cloud feedback) of the other feedback mechanisms.

If a particular feedback mechanism is an important factor in greenhouse-gas-induced climate change, it ought to play an important role in unperturbed variability as well. To take the example of water vapor feedback, suppose an internally generated forcing, such as a change in net cloud cover associated with atmospheric disturbances, were to induce a warm anomaly in the surface–troposphere system. A resulting increase in atmospheric water vapor and hence greenhouse trapping of outgoing radiation would reduce the radiative damping of the anomaly. This, in turn, will increase its magnitude. Similarly, since colder air holds less water vapor, a cold surface–troposphere anomaly ought to be associated with reduced water vapor mixing ratios. This would enhance the outgoing longwave radiation, making the anomaly cooler than if there were no decrease in water vapor. Thus while water vapor feedback plays no role in generating the temperature anomalies themselves, whether externally forced or internally generated, it ought to have a significant impact on their magnitude. In this way, water vapor feedback can be said to “enhance” or “amplify” temperature anomalies of the surface–troposphere system.

Despite its importance to the sensitivity and variability of climate, a comprehensive picture of water vapor feedback’s impact on both externally forced and internally generated climate variations is lacking. For example, it is completely unknown whether water vapor feedback amplifies an externally forced climate fluctuation, such as that arising from an increase in greenhouse gases, to the same degree that it amplifies internally generated climate variations. If this were the case, it would obviously be of enormous importance, because water vapor feedback’s contribution to the sensitivity of the climate to a greenhouse gas increase could be estimated from unperturbed variability alone. In addition, the impact of water vapor feedback on unperturbed temperature variability is itself very poorly characterized: does water vapor feedback’s strength depend on the timescale of an internally generated temperature anomaly? On its spatial scale? Addressing these fundamental issues using a coupled ocean–atmosphere model is the goal of this study. In so doing, we aim to develop a comprehensive, albeit qualitative, picture of the basic operation of water vapor feedback.

These issues have never been directly addressed before because they are impossible to study using the observed record alone. It has only been within the past few years that satellite data measuring water vapor content, outgoing longwave radiation, and surface temperature have become available. Even assuming this dataset

is accurate, it is still too short to give reliable statistics on many aspects of water vapor feedback and is likely to remain so for quite some time. A numerical model of the climate, on the other hand, provides long time series with global coverage that are reliable in a statistical sense. Moreover, a numerical model is a very flexible scientific tool because any physical mechanism it includes may be removed from the simulation and the effect of the mechanism may be diagnosed. In this study, we disable the water vapor feedback of a coupled ocean–atmosphere model by fixing the water vapor mixing ratios to their climatological mean values in the longwave portion of the model’s radiative transfer subroutine. Thus anomalies in water vapor predicted by the model’s hydrological component are not taken into account in the longwave radiative transfer calculation. In this way, if atmospheric water vapor increases due to a warm surface temperature anomaly, for example, that change in water vapor will not result in any increased greenhouse trapping. In this study, we also employ a model configuration where water vapor is allowed to interact with longwave radiation, as the model was originally designed. By comparing the variability that results from unperturbed long-term integrations of the two model configurations with and without water vapor feedback (referred to hereafter as the control and fixed H_2O configurations), we can measure directly the impact of water vapor feedback on the model’s unperturbed variability in a way that is not feasible through analysis of the observed record. Unlike the real world, we can also manipulate at will the concentrations of greenhouse gases in a numerical model. Thus we can measure the warming that results in the control and fixed H_2O configurations when CO_2 is gradually increased and then held fixed at twice its original value. This, in turn, allows us to compare the role of water vapor feedback in greenhouse-gas-induced global warming to its role in unperturbed variability. Since the suppression of unperturbed variability and the reduction of global warming in the fixed H_2O model are attributable to the same physical mechanism, our approach is self-consistent.

The presentation of this study is structured as follows. First, we give a detailed description of the numerical model (section 2) and the experimental technique (section 3) used in these simulations. In section 4, the analysis of water vapor feedback’s role in unperturbed variability is presented. The main focus in this section is the dependence of water vapor feedback’s strength on the time and spatial scale of the temperature anomaly it affects. In section 5, the results of the global warming experiments are given and comparisons are made between the contributions of water vapor feedback to climate sensitivity in the unperturbed variability and global warming contexts. Then, in section 6, we examine the way in which other feedback mechanisms, such as albedo and cloud feedback, alter the apparent impact of water vapor feedback in both the unperturbed variability and global warming contexts. Section 7a outlines the

main conclusions of the analysis. Finally, in section 7b, we place the fixed H_2O and control simulations in the context of the real climate. By comparing the unperturbed temperature variability of the fixed H_2O and control simulations to the observed temperature record, we assess whether the model's water vapor feedback is necessary to simulate the observed levels of variability.

2. Model structure and time integration

The most important features of this model are described in some detail in Manabe et al. (1991). It consists of a general circulation model of the world ocean coupled to an atmospheric general circulation model through exchange of heat, water, and momentum. The model includes those features of the earth's geography that its resolution permits. It also has a seasonal cycle of insolation, although the diurnal cycle is not included.

The variables of the atmospheric component are represented in the horizontal by a series of spherical harmonics and corresponding gridpoint values. Fifteen zonal waves and associated Legendre functions are included in the integration (Orszag 1970; Gordon and Stern 1982). When the atmospheric data is transformed from spectral space to real space for the purposes of analysis, this resolution results in a grid box size of about 4.5° lat $\times$ 7.5° long. In the vertical, finite differencing is used at nine unevenly spaced levels. The radiative transfer calculation includes the effects of clouds, water vapor, carbon dioxide, and ozone on both incoming and outgoing radiation. The sky is overcast whenever the relative humidity exceeds a critical level; otherwise clear sky is predicted. While the distribution of water vapor is predicted by the model, carbon dioxide concentration is taken to be constant, except in the global warming experiments described below. Ozone is specified as a function of latitude, height, and time of year, following observations given by Hering and Borden (1965). At the land surface, the model computes budgets of snow, water, and heat. Soil moisture is parameterized using a "bucket" model: At every land surface grid point, water is accumulated through precipitation and depleted through evaporation in a bucket whose surface area is the same as the grid box. At any given time, if the water depth in the bucket exceeds 15 cm, runoff is predicted. Otherwise, soil moisture is given by the depth of the water in the bucket.

The finite-difference oceanic component, with a horizontal resolution of 4.5° lat $\times$ 3.75° long and 12 vertical levels, uses the modular ocean model (MOM) code described in Pacanowski et al. (1991). This particular version of MOM is based, in turn, on a model described by Bryan and Lewis (1979). In addition to horizontal and vertical background subgrid-scale mixing, the model has isopycnal mixing as discussed by Redi (1982) and Tziperman and Bryan (1993). Convection occurs whenever the vertical stratification becomes unstable.

Sea ice is predicted using a free drift model developed by Bryan (1969).

At the beginning of time integration, the model's atmosphere and ocean are both individually in equilibrium with realistic seasonal and geographical distributions of sea surface temperature, sea surface salinity, and sea ice. However, as the integration proceeds, the model's climate usually drifts toward its own, less realistic, equilibrium state. This distorts the simulated variability that this study seeks to diagnose. Moreover, it would be difficult to interpret a global warming experiment where the radiative forcing perturbation is applied to a basic-state climate that is already diverging significantly from the present-day equilibrium state. Therefore, to minimize the climate drift, the fluxes of heat and water obtained from the atmospheric component of the coupled model are modified by given amounts before they are imposed upon the ocean surface. While these adjustments vary seasonally and geographically, they do not vary from year to year. Therefore, they are not correlated to the transient sea surface temperature and salinity anomalies that develop over the course of the coupled integration. Thus flux adjustment is unlikely either to amplify or damp these anomalies in a systematic way. Although the adjustments do not eliminate the shortcomings of the model (Marotzke and Stone 1995), they do prevent rapid drift of the simulated climate from realistic initial conditions. Using this flux adjustment technique, only very small trends associated with climate drift remain. For example, over the entire period of the 1000-yr integration, the fixed H_2O run exhibits a cooling trend of $0.009^\circ\text{C century}^{-1}$ in global-mean surface temperature. A trend of a similar magnitude exists in the 1000-yr control run ($0.035^\circ\text{C century}^{-1}$). For the purposes of the analysis of the model's unperturbed variability, all such linear trends were first removed from the data.

3. Experimental design

As noted in section 1, this model was integrated in two configurations to test the effects of water vapor feedback. In both cases, water vapor is variable in the hydrologic component of the model, meaning that simulated clouds and precipitation are based on humidity values predicted by the model. In the fixed H_2O configuration, however, water vapor mixing ratios at all grid points and all nine vertical levels are fixed to their climatological mean, seasonally varying values in the longwave portion of the radiative transfer subroutine. In the control configuration, on the other hand, the water vapor values predicted by the hydrologic component are passed to the longwave subroutine. The mean water vapor field used in the fixed H_2O experiments was calculated in the following way. First, integrating only the atmospheric component of the coupled model, and using seasonally varying, climatological sea surface temperatures and sea ice as a lower boundary condition, the

daily mean values of the entire water vapor field were saved away for 50 yr. Then the values corresponding to any given day of the annual cycle were averaged over all 50 yr of the integration, providing a mean water vapor field for every day of the year. These mean values were supplied to the coupled model's longwave radiative transfer subroutine as the coupled integration proceeded through each day of the year.

It should be emphasized that since water vapor was fixed only in the longwave radiative transfer subroutine of the fixed H_2O configuration, any feedback effects due to water vapor's interaction with solar radiation are included in both configurations. The aspect of water vapor feedback relating to solar radiation is therefore not a subject of this study. However, it also constitutes a positive feedback mechanism, since water vapor absorbs solar radiation. For example, a warm surface-troposphere temperature anomaly will increase the amount of water vapor in the atmosphere and enhance the absorption of solar radiation there, thereby amplifying the warm anomaly. If we had fixed water vapor in the solar radiative transfer subroutine as well as the long wave, the fixed H_2O experiment would have had even less positive feedback and therefore less unperturbed variability and a smaller response to a doubling of CO_2 . However, this effect is quite small; the impact of the shortwave component of water vapor feedback, though positive, is approximately an order of magnitude smaller than the longwave component (Ramanathan and Coakley 1978). For the sake of simplicity, the term "water vapor feedback" refers only to the longwave feedback effects of water vapor throughout this article.

The model was integrated for 1000 yr in each configuration. These integrations will be referred to as the unperturbed variability experiments. The last 800 yr of these time series were used to analyze the effects of water vapor feedback on the model's internally generated variability. The global warming experiments were initialized using the same initial conditions as the two unperturbed variability experiments. Integrating the model in both configurations, CO_2 was then increased at a rate of 1% per year until its concentration doubled, around year 70. Thereafter it was fixed at the doubled value (720 ppm) for the remainder of the 500-yr-long experiments.

4. Spatial and timescale dependence of water vapor feedback in unperturbed variability

As mentioned in section 1, one goal of this study is to understand the spatial and timescale dependence of water vapor feedback in the unperturbed temperature variability of the surface-troposphere system. Does the contribution of water vapor feedback depend upon the geographical extent of the temperature anomaly? Does it depend on how long the anomaly persists? To simplify the analysis, we selected a single variable—surface temperature—that would be broadly representative of the

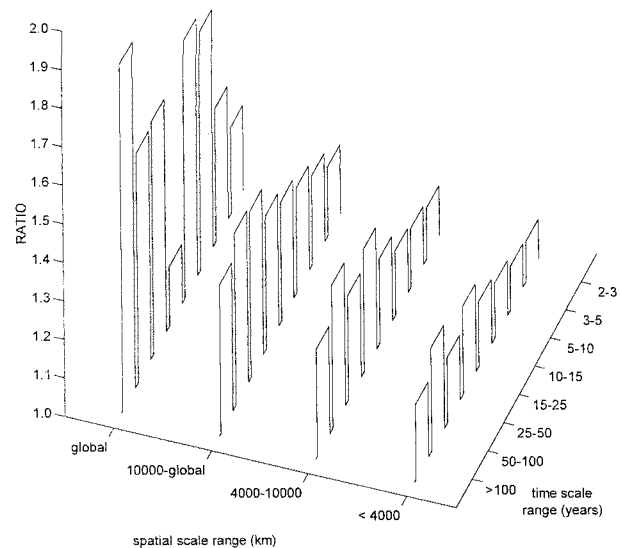


FIG. 1. The ratio control/fixed H_2O of the standard deviation of surface temperature anomalies, indicated by the heights of the bars, as a function of spatial scale and timescale. The ranges of time- and spatial scales selected for the analysis are shown in the figure. The spatial filtering required for the calculation of these ratios was performed in the following way. First, spatial filtering was carried out on the model's 48×40 grid using a Hamming digital filter in the zonal direction and a Fourier filter in the meridional direction. To select the same spatial scales at all latitudes, the digital filter varied by latitude row, taking into account the reduction in the length of a latitude circle as higher latitudes are chosen. Applying the filters in both the zonal and meridional directions to global fields of surface temperature anomalies, a new time series was produced at each grid point.

impact of water vapor feedback on these anomalies. Thus to answer these questions we compare the surface temperature variability in the fixed H_2O 1000-yr run to the control 1000-yr run on various spatial scales and timescales. Since water vapor feedback is present in the control case but absent in the fixed H_2O case, differences in variability may be ascribed to water vapor feedback. Using the following technique, it was possible to focus on any given range of spatial scales and timescales. First, the temperature anomalies of the spatial scales of interest, from 4000 to 10 000 km, for example, were selected by applying the appropriate filter in the zonal and meridional directions to each field of annual-mean temperature anomalies. Similarly, the variability corresponding to a given range of timescales, from 10 to 15 yr, for example, was extracted by bandpass filtering the resulting time series at each grid point. After applying this series of filters to both the control and fixed H_2O time series, the variability of the filtered control time series was compared to its fixed H_2O counterpart by taking the ratio of the control to fixed H_2O standard deviations at each grid point. Figure 1 depicts graphically how the global mean of this ratio changes as various spatial scales and timescales are selected. In addition, to study the role of water vapor feedback on the largest (i.e., global) spatial scale, global-mean surface

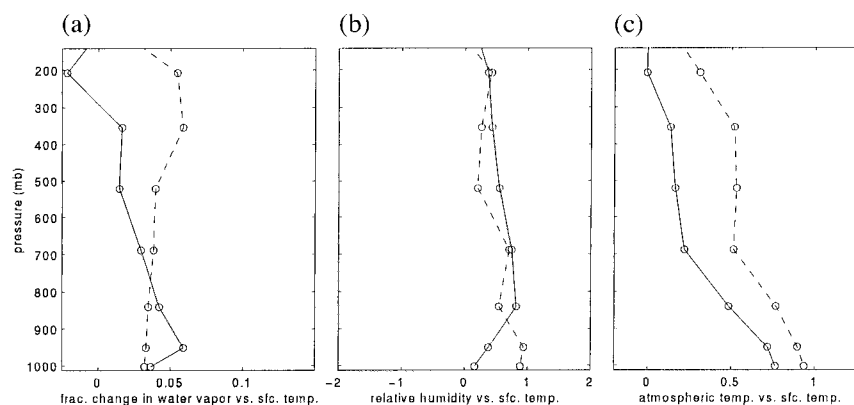


FIG. 2. The regressions between (a) fractional changes in water vapor mixing ratios and surface temperature ($^{\circ}\text{C}$), (b) relative humidity (%) and surface temperature, and (c) troposphere temperature and surface temperature in the seven lowest levels of the model (142–1013 hPa) for local (solid) and global (dashed) cases.

temperature time series were calculated for both runs. These two time series were bandpass filtered at various timescales and the variability in the control run was compared to the fixed H_2O run by taking the ratio of the two standard deviations. These ratios are also plotted in Fig. 1 for comparison with smaller spatial scales.

Two conclusions may be drawn from this figure. First, the ratio is greater than one for all time- and spatial scales, implying that there is more surface temperature variability in the control run than in its fixed H_2O counterpart on all time and spatial scales. Thus water vapor feedback is a positive feedback mechanism that enhances the internally generated surface temperature variability of this model. Second, the ratio increases as larger spatial scales and longer timescales are selected. For example, in the case of the small spatial-scale anomalies (spatial scale < 4000 km), the ratio increases from 1.10 for the 2–3-yr timescale to 1.19 for the longest timescales (> 100 yr). More importantly, the ratio generally increases very dramatically the larger the spatial scale in question. For example, on the 5–10-yr timescale, the ratio increases from 1.14 for anomalies smaller in spatial scale than 4000 km, to 1.62 for global-mean anomalies. On the longest timescales (> 100 yr) the ratio increases from 1.19 for small-scale anomalies to 1.90 in the global-mean case.

Since water vapor feedback is a positive feedback mechanism in unperturbed variability, tropospheric absolute humidity must increase (decrease) as surface temperature increases (decreases). This relationship results from the fact that the saturation mixing ratio of water vapor increases exponentially with temperature. Thus a temperature anomaly in the surface–troposphere system is associated with an anomaly of the same sign in the water-vapor-holding capacity of the atmosphere. If condensation in the troposphere and evaporation from the surface act to keep relative humidity approximately constant throughout the troposphere, then absolute humidity levels will fluctuate in phase with surface–troposphere

temperature. By testing this reasoning, we aim to explain, at least in part, the most important result from Fig. 1: that water vapor feedback is more effective at large spatial scales than small.

The argument outlined above depends on the relationships between three tropospheric variables and surface temperature: absolute humidity, relative humidity, and air temperature. Accordingly, Fig. 2 shows the regressions at every level of the model's troposphere between these variables and surface temperature. All calculations are based on annual-mean data from the control unperturbed variability experiment. To clarify how each of these quantities responds to large- and small-scale surface temperature anomalies, the regressions were calculated for two cases. In all three panels, the regressions between global-mean atmospheric variables and global-mean surface temperature are shown with a dashed line, while the global means of the local regressions, calculated separately at every grid point, are shown with a solid line. Thus the dashed lines represent the relationships between surface temperature and absolute humidity, relative humidity, and air temperature, and on the largest (global) spatial scale. On the other hand, the solid lines show how, on average, local fluctuations in these quantities relate to changes in local surface temperature. Of course, local anomalies include contributions from all spatial scales larger than a grid box, including the global scale. However, the variability at a single grid point is overwhelmingly dominated by fluctuations smaller in spatial scale than the global scale. For example, in the control unperturbed variability experiment, the global-mean standard deviation of local surface temperature is about 0.74°C , whereas the standard deviation of global-mean surface temperature is only about 0.13°C . Since the magnitude of a typical global anomaly is so much smaller than the magnitude of a typical local anomaly, fluctuations smaller in spatial scale than the global scale must be responsible for most local variability. We may therefore consider the regres-

sions shown by solid lines to represent relationships between atmospheric variables and surface temperature at spatial scales much smaller than the global scale.

We begin the discussion of these results by focusing on Fig. 2a. Regressions were calculated using fractional changes in absolute humidity, rather than absolute humidity itself, to focus directly on the impact of water vapor fluctuations on the radiative properties of the atmosphere. Since longwave absorptivity due to water vapor is approximately proportional to the logarithm of the water vapor mixing ratio in the troposphere, fractional changes in water vapor are roughly proportional to changes in atmospheric absorptivity due to water vapor. Figure 2a illustrates water vapor feedback's greater impact on large spatial scales than small in terms of this relationship. In the lower troposphere, the strength of the global-scale relationship between absorptivity due to water vapor and surface temperature is not significantly different from that of the local anomalies. However, in the mid- to upper troposphere, the situation is very different. Here, the global-scale relationship is much stronger than its local counterpart. Because of the proximity to the top of the atmosphere, changes in absorptivity here probably have a larger effect on the atmosphere's greenhouse effect than if a similar change were to occur in the lower troposphere. In any case, when the entire troposphere is considered, a given global-mean temperature anomaly induces a larger fractional increase in water vapor in the air column above than a typical local anomaly of the same magnitude.

But why are the fractional changes in water vapor per degree change in surface temperature larger in the global than the local case? Figure 2b shows that relative humidity changes very little as surface temperature fluctuates; the regressions are nearly zero throughout the troposphere for both local and the global cases. This indicates that neither local nor global surface temperature anomalies are associated in any systematic way with anomalies in relative humidity in the troposphere. The differing relationships between absolute humidity and surface temperature must therefore be explained by differences in the relationships between tropospheric temperature and surface temperature, as illustrated in the right panel. This panel shows that global-scale surface temperature anomalies penetrate much more deeply into the troposphere than their local counterparts. This is most apparent in the upper troposphere, where the regressions between atmospheric temperature and surface temperature in the global case are nearly four times as large as in the local case. Given that the same surface temperature anomalies induce virtually no change in relative humidity, this implies a larger change in absolute humidity in the global case.

The results presented in Fig. 2 explain how water vapor feedback's contribution to the radiative damping of temperature anomalies depends on their spatial scale. However, temperature anomalies of the surface-troposphere system may also be damped by horizontal ex-

change of sensible heat within the atmosphere itself. The effectiveness of this process also depends on the anomalies' spatial scale. For example, a small-scale temperature anomaly would be very effectively diffused into surrounding regions by horizontal advective heat exchange. Clearly, this diffusive damping of temperature anomalies is less effective the larger the anomaly's spatial scale. At the global scale, of course, it is nonexistent. Since water vapor feedback operates exclusively on the radiative component of the damping, the impact of water vapor feedback on small spatial scales may be smaller simply because the relative contribution of radiative damping to the total damping is smaller. This constitutes another explanation for the spatial scale dependence of the ratio plotted in Fig. 1. It should also be pointed out that advective processes in the atmosphere are also the main reason why the regressions of local atmospheric temperature and surface temperature, shown in Fig. 2c, are smaller than their global-mean counterparts. This, in turn, is responsible for the weaker water vapor feedback in the case of the local anomalies. Thus advection not only contributes heavily to the damping of small-scale surface temperature anomalies, obscuring the effects of water vapor feedback, but it also weakens water vapor feedback itself.

Temperature anomalies are damped by evaporative fluxes across the air-surface interface as well. This process is also likely to be more effective at small spatial scales due to the increasing effects of advection as spatial scales decrease. For example, while a warm global-scale anomaly may be associated with enhanced evaporation at the surface, this latent heat must ultimately be released in the atmosphere. This would result in an enhancement of the warm anomaly in the troposphere, which must in turn warm the surface through enhanced radiative and sensible heat fluxes, counteracting the cooling effect of the initial evaporative flux. The net damping effect of the evaporative flux on the global-mean surface-troposphere temperature anomaly is therefore limited. A small-scale warm anomaly would also result in enhanced evaporation. Although this latent heat must be released somewhere in the atmosphere, it may be released at a different location, resulting in an export of heat out of the region of the anomaly. In this case, the effect of the initial evaporative flux at the surface would be to damp the entire surface-troposphere anomaly. Thus evaporative damping may also obscure the effects of water vapor feedback at small scales by decreasing the relative contribution of radiative processes to the total damping.

We have seen how and why water vapor feedback affects internally generated surface temperature variability on various spatial scales. We now verify that water vapor feedback actually alters the top-of-the-atmosphere, longwave radiative damping of these anomalies in a manner consistent with its impact on their variability. The first row of the first column of Table 1 shows the regression between global-mean, clear-sky

TABLE 1. The regressions between global-mean clear-sky outgoing longwave radiation and global-mean surface temperature (first row) and the global-mean of the regressions between local clear-sky outgoing longwave and local surface temperature (second row). The third column shows the difference in the regressions between the control and fixed H_2O cases.

	Control	Fixed H_2O	Difference
Global anomalies			
$W\ m^2\ (^{\circ}C)^{-1}$	1.97	2.69	0.72
Local anomalies			
$W\ m^2\ (^{\circ}C)^{-1}$	1.42	1.92	0.50

outgoing longwave radiation and global-mean surface temperature for the control unperturbed variability experiment. Immediately below is the global-mean of the regressions between local clear-sky outgoing longwave and local surface temperature. These two values represent the change in the clear-sky longwave flux at the top of the atmosphere per unit change in surface temperature on both the local and the global scale. This is a measure of the strength of the radiative damping of surface temperature. By examining clear-sky fluxes, we eliminate the effects of cloud feedback. The second column presents the results of the same calculations for the fixed H_2O experiment. Finally, the third column shows the difference in the regressions between the control and fixed H_2O cases. In both the local and the global cases, the regressions are larger for the experiment without water vapor feedback; the presence of water vapor feedback in the control experiment reduces the longwave damping of both local and global temperature anomalies. In the global case, water vapor feedback reduces the damping by $0.72\ W\ m^{-2}\ ^{\circ}C^{-1}$, the difference between the two regressions, whereas in the local case, the damping is reduced by $0.50\ W\ m^{-2}\ ^{\circ}C^{-1}$. The reduction is larger for the global-mean case, which is consistent with the observation that water vapor feedback is more effective the larger the spatial scale.

5. Water vapor feedback and global warming

We wish to examine the role of water vapor feedback in global warming as well as unperturbed variability. As described in section 3, global warming experiments were performed integrating the model in both configurations. Carbon dioxide was increased starting at the beginning of the two integrations a rate of $1\%\ yr^{-1}$ until its concentration doubled around year 70. Thereafter it was fixed at its doubled value (720 ppm). Just as in the analysis of unperturbed variability presented in section 4, we analyzed surface temperature to diagnose the climate change in the two experiments. Figure 3 shows the 500-yr annual-mean time series of the global-mean surface temperature change in these integrations relative to the unperturbed variability experiments, where CO_2 is fixed at 360 ppm. In both the fixed H_2O and control cases, there is a steady warming for the first 70 yr. After year 70, the warming continues but at a much slower

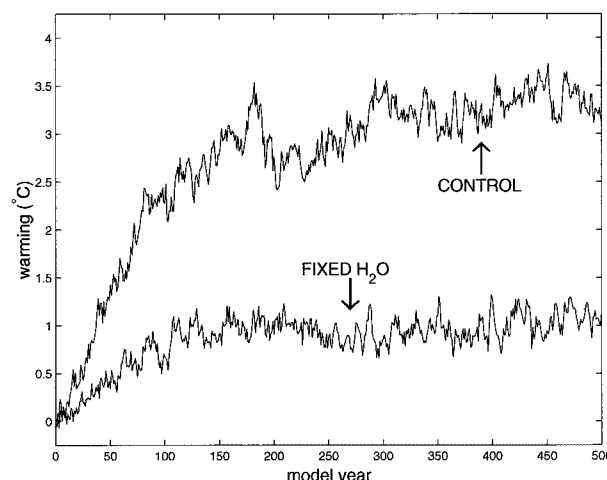


FIG. 3. The 500-yr annual-mean time series of the global-mean surface temperature change in the integrations where CO_2 is doubled to 720 ppm relative to the unperturbed variability experiments, where CO_2 is fixed at 360 ppm.

rate for the remainder of the experiments. If the integrations were continued beyond year 500, both climates would likely continue to change slowly for several centuries in response to the new CO_2 value. However, enough of the climate change has occurred by this point that we may consider the climates toward the end of these integrations to be broadly representative of their equilibrium response to the increase in CO_2 . It is clear from the figure that the magnitude of the warming is much larger in the model that contains water vapor feedback than the model that does not: The warming averaged over the last century of the integrations is $3.38^{\circ}C$ in the control case, while it is only $1.05^{\circ}C$ in the fixed H_2O case.

These results demonstrate that water vapor feedback is positive in the global warming case just as it is positive in the context of unperturbed variability. However, the amount by which water vapor feedback amplifies global warming is larger than the amount by which it amplifies the magnitude of a typical internally generated surface temperature anomaly. Since standard deviation is a measure of the magnitude of a typical anomaly, this may readily be seen by comparing the ratio (control/fixed H_2O) of standard deviation of surface temperature to the ratio of the warming. If water vapor feedback is equally effective in both, then the ratios should be identical. Since CO_2 -induced warming occurs on a global scale, and because of the spatial-scale dependence of water vapor feedback documented in section 4, we compare the warming ratio to the ratio of standard deviation of global-scale temperature fluctuations. The warming ratio is $3.38^{\circ}C/1.05^{\circ}C = 3.2$. However, the ratio of standard deviation of global-mean, annual-mean surface temperature is 1.53. Thus water vapor feedback is more than twice as effective in enhancing global warming as

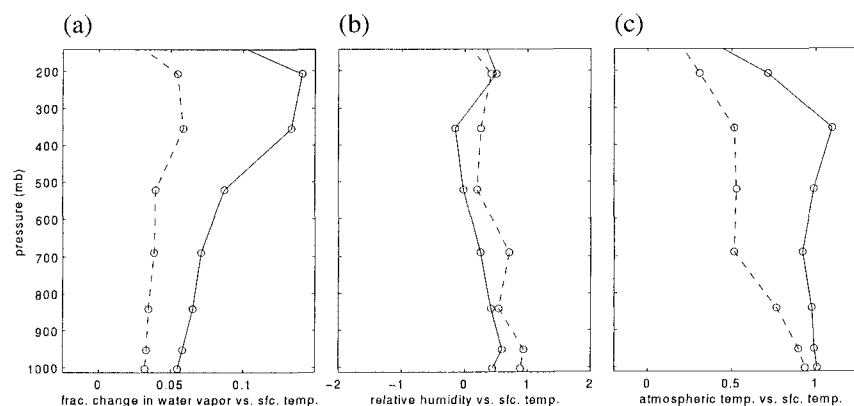


FIG. 4. As in Fig. 2, (a) the relationships between fractional changes in water vapor and surface temperature ($^{\circ}\text{C}$), (b) the relationships between relative humidity (%) and surface temperature, and (c) the relationships between tropospheric temperature ($^{\circ}\text{C}$) and surface temperature. In all three panels, the solid lines indicate the relationships between atmospheric variables and surface temperature for the global warming case. The dashed lines show the regressions between global-mean values and global-mean surface temperature from the control unperturbed variability experiment. Note that Fig. 4 has the same aspect ratio and axes as Fig. 2.

it is in amplifying internally generated, global-mean temperature anomalies.

In section 4 we explained why the effectiveness of water vapor feedback depends on spatial scale by examining the relationships between surface temperature on the one hand and fractional changes in absolute humidity, relative humidity, and tropospheric temperature on the other. Using identical methods, we now explain why water vapor feedback is so much more effective in global warming than unperturbed variability. In direct analogy to Fig. 2, Fig. 4 shows the relationships between fractional changes in water vapor and surface temperature, relative humidity and surface temperature, and tropospheric temperature and surface temperature. All of the dashed curves indicate regressions between global-mean, annual-mean values from the control unperturbed variability experiment. They are therefore identical to the dashed curves in Fig. 2. The solid lines, while not regressions, indicate the analogous relationships between atmospheric variables and surface temperature for the global warming case. In the case of atmospheric temperature (right panel), these values were calculated by subtracting the global-mean tropospheric temperatures averaged over years 401–500 of the control unperturbed variability experiment from the global-mean tropospheric temperatures averaged over years 401–500 of the control global warming experiment. The differences were then divided by the difference in global-mean surface temperature averaged over the same time period. The resulting ratios therefore represent the warming that takes place in the troposphere per degree surface temperature warming, just as the regressions represented by the dashed lines indicate the tropospheric temperature changes that take place per degree surface temperature fluctuation. The relationships between relative humidity and surface temperature (middle panel)

were calculated in a similar fashion. The values indicated by the solid line in the left panel were calculated by first taking the difference between the global-mean mixing ratios averaged over years 401–500 of the control global warming and unperturbed variability experiments and dividing by the average mixing ratios from the unperturbed variability experiment. Finally, these fractional changes in water vapor were divided by the difference in global-mean surface temperature between the two experiments.

First, we compare the relationships between the fractional changes in water vapor and surface temperature for global-scale unperturbed variability and the global warming, shown on the left in Fig. 4. As described in section 4, this is approximately equivalent to analyzing the relationship between atmospheric absorptivity due to water vapor and surface temperature. At all levels of the troposphere, there is a strong positive relationship between fractional changes in water vapor and surface temperature for both the unperturbed variability and global warming cases. However, for a given change in surface temperature, a much larger fractional change in water vapor occurs in the global warming case. Although this is true at all levels of the troposphere, it is most apparent in the upper troposphere, where changes in absorptivity probably have a larger effect on the atmosphere's greenhouse effect than if a similar change were to occur in the lower troposphere. This evidence is consistent with the fact that water vapor feedback is more effective in enhancing global warming than in amplifying internally generated, global-mean anomalies.

We have already established that, throughout the troposphere, there is no systematic relationship between internally generated, global-mean relative humidity and surface temperature anomalies. The middle panel of Fig.

4 shows that relative humidity also changes very little as the surface warms in response to increased CO_2 . There is a very small increase of a few tenths of a percent per degree warming in the lower troposphere, while in the mid- to upper troposphere, the relationship falls off nearly to zero. Thus in both the unperturbed variability and global warming cases, surface temperature anomalies have very little effect on tropospheric relative humidity.

Given that the relative humidity anomalies associated with surface temperature anomalies are small in both unperturbed variability and global warming cases, the degree to which a surface temperature anomaly penetrates the troposphere must be a critical factor in determining the strength of the water vapor feedback. We now examine both the vertical structures of the warming in the global warming experiment and temperature anomalies in the unperturbed variability experiment, shown in Fig. 4c. In both cases, there is a strong relationship between temperature anomalies aloft and temperature anomalies at the surface. However, the relationship is much stronger in the global warming case, where the warming is nearly uniform throughout the entire troposphere. In the unperturbed variability case, on the other hand, the regression between tropospheric temperature and surface temperature decreases from almost 1 near the surface to about 0.3 at 200 hPa. Internally generated, global-mean temperature anomalies do not penetrate as effectively into the troposphere as warming induced by a doubling of CO_2 . Thus for a CO_2 -induced warming and an internally generated warm anomaly of the same magnitude, the fact that relative humidity changes very little in both cases implies a much larger increase in upper-tropospheric water vapor mixing ratios in the global warming case than the unperturbed variability case. This implies a stronger water vapor feedback to global warming.

Since the degree to which a surface temperature anomaly penetrates the troposphere is such a critical factor in determining the strength of its associated water vapor feedback, it is desirable to gain an understanding of why internally generated, global-mean temperature anomalies do not penetrate as effectively into the troposphere as the warming induced by a doubling of CO_2 . To shed light on this issue, we examined the characteristic horizontal structure of both global-scale unperturbed temperature variability and global warming at every level of the model's troposphere. To see how the characteristic horizontal structure of internally generated, global-mean temperature anomalies changes with height, we calculated regressions between local and global-mean temperature at each level of the troposphere using annual-mean data from the control unperturbed variability experiment. To simplify the presentation of these results, we then computed the mass-weighted average of these regressions over two layers of the troposphere, one corresponding to the lower troposphere (770–1013 hPa), and the other corresponding

to the mid- and upper troposphere (273–770 hPa). The geographical distribution of these regressions for both layers is shown in Fig. 5. The patterns for both layers are very similar to the patterns for their constituent levels and are therefore broadly representative of the change with height in the horizontal structure of global-mean temperature anomalies. We also performed an analogous calculation for the global warming case. We first computed the warming due to a doubling of CO_2 at each grid point and each vertical level of the troposphere by taking the difference in temperature between the control global warming and unperturbed variability experiments averaged over the fifth century of both integrations. Then, at each vertical level, we divided these values by the global-mean warming at that level. Finally, we calculated the mass-weighted average of these ratios over the lower (770–1013 hPa) and mid- to upper (273–770 hPa) troposphere, as before. The geographical distribution of these values is shown in Fig. 6.

We begin the discussion of these calculations by examining the unperturbed variability case. Figure 5b reveals that global-mean temperatures in the lower troposphere are dominated by contributions from midlatitude land locations, the high latitudes of the Southern Hemisphere, and a region stretching from the equatorial to the southeastern tropical Pacific. Thus when global-mean lower-tropospheric temperature is anomalously warm, these regions also tend to be warm. The regression pattern for surface temperature (not shown) is very similar. At the same time, Fig. 5a shows that when global-mean temperatures in the upper troposphere are warm, temperatures in other regions—mainly a wide band stretching across nearly the entire world from 30°N to 30°S—tend to be warm. Thus the regions contributing most to global-mean variability shift markedly as one goes from the surface and lower troposphere to the mid- and upper troposphere. Temperature variability in the regions that dominate the mid- and upper-tropospheric global-mean variability is most likely only weakly related to the variability in the distant regions that dominate the global-mean variability at the surface and in the lower troposphere. This explains the substantial decrease with height in the regression between global-mean tropospheric temperature and surface temperature seen in the dashed line of Fig. 4c.

A very different picture emerges from the global warming case. Figure 6b shows that, in the lower troposphere, warming is larger than the global-mean value in the mid- to high latitudes of both hemispheres, while it is less than the global-mean value in much of the midlatitudes and Tropics. The ratio pattern at the surface (not shown) is very similar. Figure 6a also reveals a similar pattern for the mid- and upper troposphere, although the equator-to-pole contrast in the ratio is somewhat smaller. Thus where warming is large at the surface and in the lower troposphere, it is also large in the mid- and upper troposphere. This confirms that the uniform global-mean tropospheric warming seen in the solid line

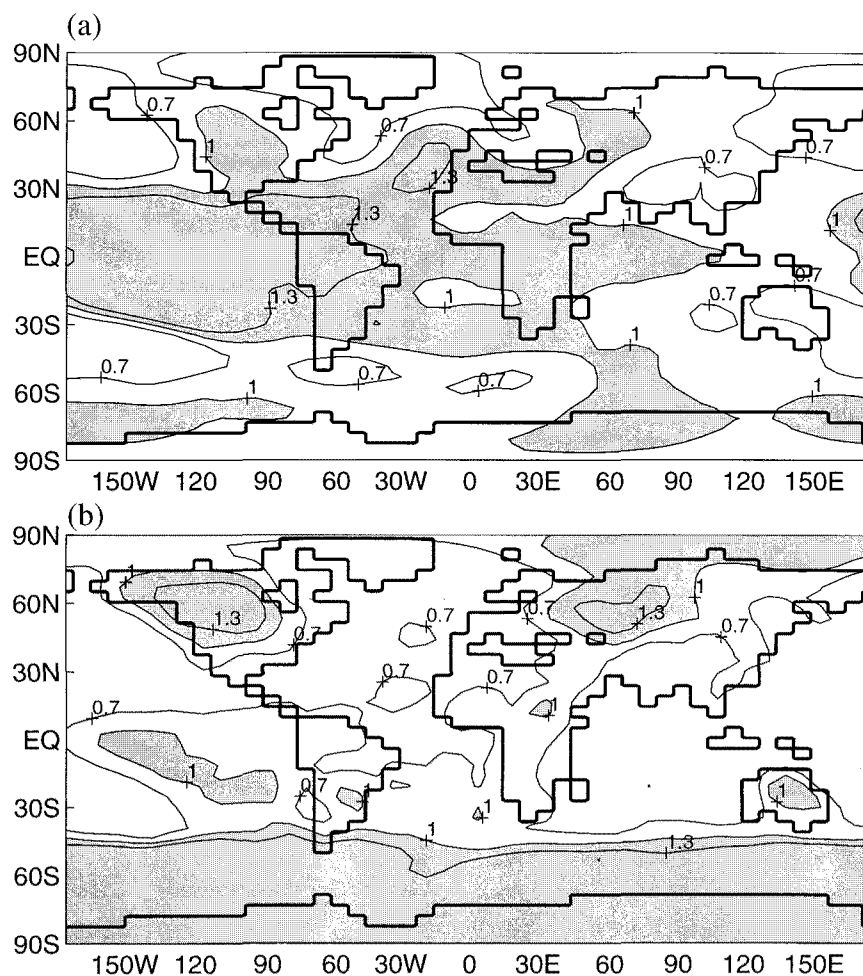


FIG. 5. The geographical distribution of the mass-weighted, vertically averaged regressions between local and global-mean temperature from the control unperturbed variability experiment for two cases. (a) Averaged over the mid- to upper troposphere (273–770 hPa). (b) Averaged over the lower troposphere (770–1013 hPa). Regions where the regressions exceed 1 are shaded.

of Fig. 4c also has a horizontal structure that is uniform with height. A warming at a given location is associated with a very similar warming aloft and therefore induces a large water vapor feedback. This is because global warming is the climate response to a steady, globally uniform forcing. Conversely, internally generated, global-mean temperature anomalies are a superposition of many modes of variability, whose individual impact is not geographically uniform, and that may not affect all parts of the troposphere equally. Thus the horizontal structure of an internally generated, global-mean anomaly does not persist as height increases and the water vapor feedback to such an anomaly is accordingly weaker.

6. Interaction between water vapor and other feedbacks

In section 5, we showed that water vapor feedback amplifies the model's global warming response to a

doubling of CO_2 by a factor of 3.2. This is substantially greater than previous estimates of the impact of water vapor feedback. For example, Manabe and Wetherald (1967) showed that a radiative-convective model where relative humidity is fixed (analogous to our control model) was about twice as sensitive to an external forcing as a fixed absolute humidity model (analogous to our fixed H_2O model). Using nearly identical techniques, other modeling studies have arrived at similar results (see Ramanathan and Coakley 1978): water vapor feedback amplifies the climate response to an external forcing by approximately a factor of 2. Extrapolating from Raval and Ramanathan's (1989) observational estimate of the strength of water vapor feedback, Cess (1989) calculated that water vapor feedback would amplify CO_2 -induced global warming by a factor of about 1.6. Although this calculation may not be perfectly accurate, since Raval and Ramanathan's estimate is based on the geographical variation of water vapor and surface temperature during only one month,

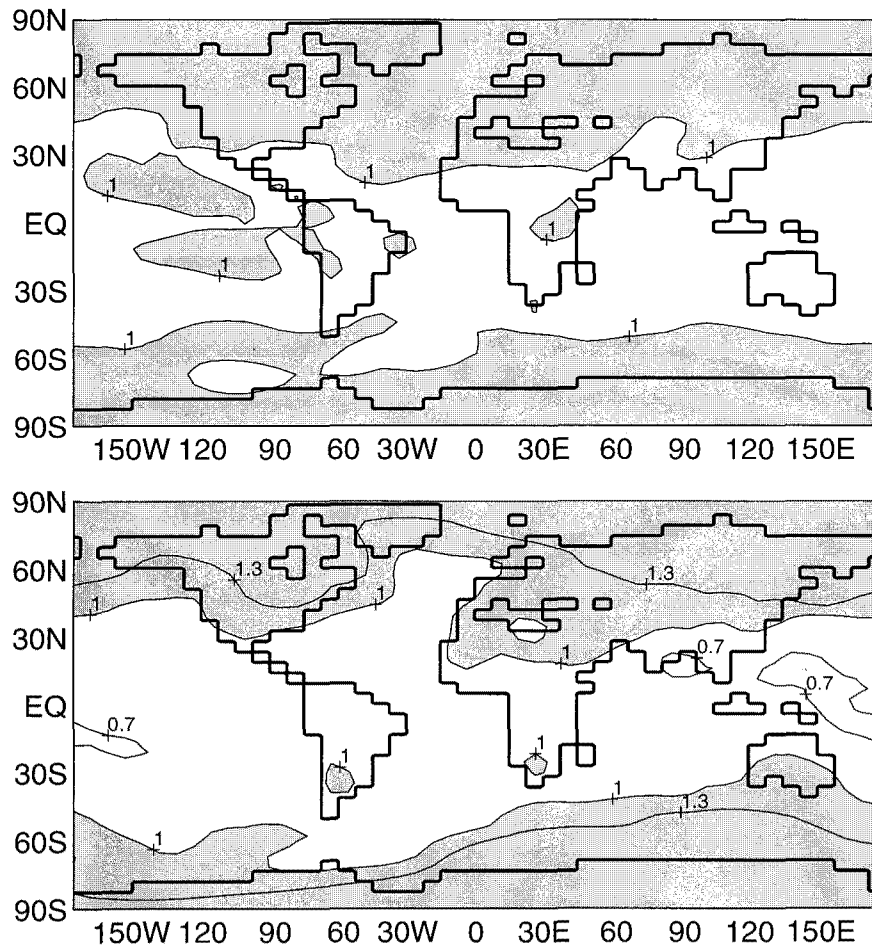


FIG. 6. The geographical distribution of the mass-weighted, vertically averaged ratio between local and global-mean warming due to CO_2 doubling for two cases. (a) Averaged over the mid-to upper troposphere (273–770 hPa). (b) Averaged over the lower troposphere (770–1013 hPa). Regions where the ratio exceeds 1 are shaded.

it is nevertheless much lower than 3.2. In this section, we explain the discrepancy between our estimate of water vapor feedback's impact and those of previous studies.

The interaction between water vapor feedback and other feedback mechanisms is not taken into account in any of the above-mentioned studies. However, the model considered here does contain other feedback mechanisms, such as albedo and cloud feedback, that alter the impact of water vapor feedback. We may illustrate this point mathematically. Let T'_c be the equilibrium global warming response of the control model to a thermal forcing Q . Response T'_c can be related to Q through the sensitivity parameter of the control climate, Λ_c :

$$T'_c = \frac{Q}{\Lambda_c}. \quad (1)$$

An identical relationship exists among the equilibrium global warming response in the fixed H_2O model

(T'_f), the same thermal forcing Q , and the sensitivity parameter of the fixed H_2O climate, Λ_f :

$$T'_f = \frac{Q}{\Lambda_f}. \quad (2)$$

Thus the ratio of the warming in the two climates equals the inverse ratio of the sensitivities:

$$\frac{T'_c}{T'_f} = \frac{\Lambda_f}{\Lambda_c}. \quad (3)$$

We may rewrite Eq. (3) by expanding the sensitivity parameters in terms of contributions from various feedback mechanisms:

$$\frac{T'_c}{T'_f} = \frac{\Lambda_f}{\Lambda_c} = \frac{\lambda_o - \sum_f \lambda}{\lambda_o - \lambda_{w,hw} - \sum_c \lambda}. \quad (4)$$

Here λ_o represents the climate sensitivity parameter

that would result if no feedback mechanisms were in effect. This value is the change in outgoing longwave per degree centigrade that results from the temperature increase alone, as given by the Stefan–Boltzmann law. The mean climate for the two experiments prior to CO₂ doubling is nearly identical, so λ_o may be taken to be the same for both experiments. The variable $\lambda_{w,lv}$, which applies only to the control model, is the change to λ_o owing to the longwave effects of water vapor feedback. Here, $\Sigma_c \lambda$ and $\Sigma_f \lambda$ are the modifications to λ_o that arise from the other feedback mechanisms in the control and fixed H₂O models, respectively. They each include contributions from albedo, cloud, and lapse rate feedbacks, which may not have the same strength in the two models.

We now divide both the numerator and the denominator of equation 4 by λ_o , which gives the contributions of feedback mechanisms to the two climate sensitivities in terms of nondimensional gain factors:

$$\frac{T'_c}{T'_f} = \frac{1 - \sum_f g}{1 - g_{w,lv} - \sum_c g}. \quad (5)$$

It is clear from Eq. (5) that impact of water vapor feedback, as measured by the ratio of the warmings, is affected not only by $g_{w,lv}$, the nondimensional longwave water vapor feedback parameter, but also by the contributions of other feedback mechanisms, as given by $\Sigma_c g$ and $\Sigma_f g$. For this reason, it is desirable to understand how all feedback mechanisms contribute to the sensitivities of the control and fixed H₂O climates. In so doing, we aim to explain why our estimate of water vapor feedback's impact is so much larger than previous estimates.

To carry out this quantitative evaluation of all feedback mechanisms, we calculated the radiative effects of the simulated changes in lapse rate, water vapor, cloudiness, and surface albedo upon CO₂ doubling using an off-line version of the model's radiative transfer subroutine. Starting with the temperature, water vapor, cloudiness, and surface albedo distributions averaged over years 401–500 of the unperturbed variability experiments, we calculated the global-mean net incoming solar and outgoing longwave radiation at the top of the atmosphere. Then, to focus on a particular feedback mechanism, we performed a second off-line calculation. For example, to assess the control model's albedo feedback, we imposed the mean surface albedo averaged over years 401–500 of the control global warming experiment and recalculated the net incoming global-mean solar radiation at the top of the atmosphere. We then divided the change in net incoming solar radiation resulting from the surface albedo decrease by the global-mean surface temperature change due to CO₂ doubling (3.38°C). This gave λ_a , the contribution of albedo feedback to the $\Sigma_c \lambda$ terms shown in Eq. (4). Finally, we divided λ_a by λ_o , calculated based on the global-mean

TABLE 2. The gain factors for lapse rate, water vapor, cloud, and surface albedo feedbacks as calculated using the off-line radiation code.

	Control	Fixed H ₂ O
Lapse rate (g_l)	0.17	0.24
Water vapor (g_w)	0.39	0.07
Cloud (g_c)	0.14	0.10
Sfc. albedo (g_a)	0.12	0.11
Correction	0.01	–0.00

emission temperature of the model climate. This gave the gain factor g_a for albedo feedback. An analogous calculation was carried out for cloud and water vapor feedback. To quantify lapse rate feedback, the increase in global-mean outgoing longwave radiation at the top of the atmosphere due to the CO₂-induced temperature change was divided by the temperature increase itself. This value was then subtracted from λ_o , the change in outgoing longwave radiation per degree Kelvin expected from the Stefan–Boltzmann law, thereby isolating the effects of CO₂-induced changes in the vertical temperature structure. The entire procedure was repeated for the fixed H₂O case for all feedbacks, except that the change in water vapor upon CO₂ doubling was not allowed to affect longwave radiation in the assessment of water vapor feedback.

The resulting values for the gain factors are shown in Table 2. The gain factors for lapse rate feedback are quite large in both models due to the large stratospheric cooling that occurs when CO₂ doubles. This reduces outgoing longwave radiation at the top of the atmosphere, thereby making lapse rate feedback positive. The gain factor is somewhat larger in the fixed H₂O case because the stratospheric cooling is nearly identical in both models, so that the reduction in outgoing longwave radiation on a per degree centigrade basis is larger in the experiment with less warming. The fact that lapse rate feedback is positive and has a stronger effect in the model without water vapor feedback is a consequence of our choice to analyze the changes in radiative fluxes due to feedback mechanisms at the top of the atmosphere, rather than at the tropopause, as is often done. This unfortunately combines the effects of CO₂-induced stratospheric cooling, which is not normally thought of as contributing to lapse rate feedback, and tropospheric lapse rate changes, which are. However, we were compelled to choose the top of the atmosphere as our reference level because of the difficulty of calculating radiative fluxes at the tropopause, which is often ill defined at high latitudes (Wetherald and Manabe 1988). The gain factor for water vapor feedback is slightly positive in the fixed H₂O case because of the shortwave effect of water vapor feedback discussed in section 3. This effect also exists in the control case and is of similar magnitude (0.06). The remainder of the control gain factor is due to the longwave effects of water vapor. The gain factor for cloud feedback is positive in both

models. This is consistent with the results of Wetherald and Manabe (1988), who showed that the cloud feedback related to CO_2 doubling in an atmosphere-mixed layer model whose atmospheric component is very similar to the present model is positive. In fact, the gain factor they calculate is very close to ours (0.11). Although the cloud feedback is slightly stronger in the control model, it is encouraging that the control and fixed H_2O gain factors agree as well as they do. This demonstrates that eliminating water vapor feedback has only a small effect on the magnitude of cloud feedback. The gain factors for albedo feedback are also very similar between the two models, although this is not surprising, since the models have approximately the same mean climate and therefore approximately the same mean sea ice and snow distributions.

In addition to the calculations discussed above, the temperature, water vapor, cloud, and surface albedo changes from the global warming experiments were imposed simultaneously and the global-mean, top-of-the-atmosphere solar and longwave radiative effects of these combined changes were computed using the off-line radiation code. These were then compared to the sum of the radiative effects of the temperature, water vapor, cloud, and surface albedo changes calculated separately. The difference between these two quantities, when divided by the global warming in the two experiments, provided corrections to Λ_c and Λ_f that arise from the radiative interaction of the feedback mechanisms. These corrections were in turn converted to gain factor corrections through division by λ_a . These values are listed in the last row of Table 2. The fact that these corrections are very small relative to the other gain factors is evidence that the feedback mechanisms can be measured separately through their effect on the atmosphere's radiative balance and then combined in a linear fashion without large error.

The radiative interaction of feedback mechanisms is small enough that their associated gain factors may be combined linearly to a fairly good approximation; however, the impacts of feedback mechanisms on the climate's temperature response to an external radiative forcing do not add up linearly, as predicted by Eq. (5). This point may be made more concrete by examining the ratio of the warmings predicted by the gain factors in Table 2. If the gain factors are inserted into Eq. (5), the ratio of the warmings is about 2.8, quite close to the actual ratio of 3.2. However, if the effects of cloud and albedo feedback, both of which are positive feedback mechanisms in this model, are removed from the calculation, the ratio falls to 1.6. Thus the presence of other positive feedback mechanisms enhances the impact of water vapor feedback on the warming. This is why our estimate of the effect of water vapor feedback on global warming is so much larger than previous estimates. This effect may also be seen by examining the geographical dependence of the CO_2 -induced warming in the present models. Figure 7a shows the geographical

distribution of the ratio (control/fixed H_2O) of the local surface warming that occurs by the final century of the global warming experiments. This plot represents the geographical dependence of water vapor feedback's impact on global warming. It is clear from the figure that water vapor feedback has its largest impact at high latitudes. In fact, the ratio of the warmings exceeds 4 over a significant portion of the globe poleward of 50° , especially in the Southern Hemisphere. This is precisely the part of the model world where snow and sea ice are present, especially in the winter. The reason why water vapor feedback has such a strong effect in these regions is because another important positive feedback mechanism, albedo feedback, is present here but not elsewhere.

Although it is not known whether the greenhouse-gas-induced change in cloudiness is a positive or negative feedback to surface temperature in the real climate, we have already noted that cloud feedback is positive in the context of the global warming simulated by both models. This result is consistent with the fact that the ratio of the warmings shown in Fig. 7a is somewhat larger than 2 even over most midlatitude and tropical locations, whereas the ratio predicted by the off-line version when both cloud and albedo feedback are absent was significantly less than 2 (1.6). Thus both cloud and albedo feedback enhance the impact of water vapor feedback in the global warming simulations. Our estimate of water vapor feedback's effect on global warming must therefore be viewed only in the context of the model's other feedback mechanisms. If the albedo or cloud feedbacks had been different in our model, the ratio of the warmings would also have been different.

Other feedback mechanisms affect the apparent impact of water vapor feedback in the unperturbed variability experiments as well. Our estimate of the strength of water vapor feedback in unperturbed variability, based on the control/fixed H_2O ratio of standard deviation of surface temperature, must therefore also be viewed in the context of the model's other feedback mechanisms. For example, the enhancement of water vapor feedback by albedo feedback may be seen by comparing the internally generated local variability of the two models. Figure 7b shows the geographical distribution of the ratio (control/fixed H_2O) of the standard deviation of annual-mean surface temperature. Much of the high latitudes are covered by shaded regions, where the ratio exceeds 1.3. Water vapor feedback has a larger impact on the variability at these locations because albedo feedback comes into play. An analysis of the reason behind the large maximum in the ratio of the variability in the equatorial Pacific is beyond the scope of this paper. However, a model very similar to the control model is known to simulate a phenomenon resembling ENSO (see Knutson et al. 1997). Preliminary analysis, to be presented in a future paper, indicates that fixing water vapor in the radiative transfer subroutine suppresses significantly the model's ENSO-like phenome-

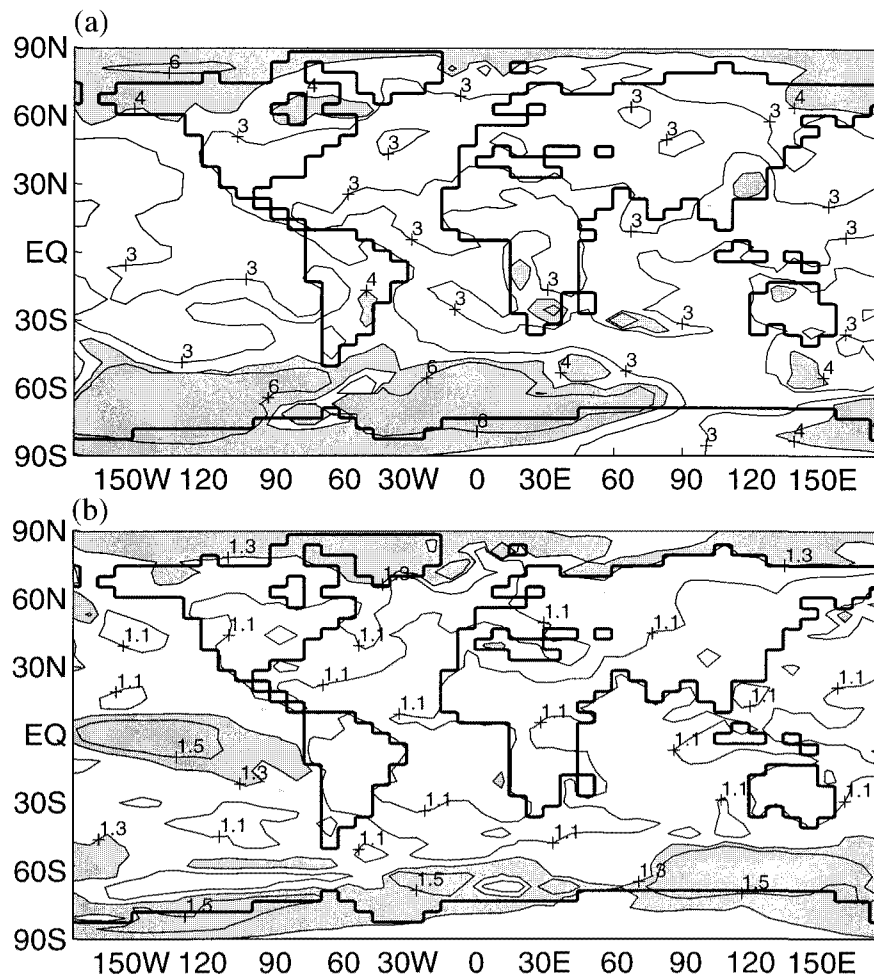


FIG. 7. (a) The geographical distribution of the ratio (control/fixed H₂O) of the local surface warming that took place in the global warming experiments. The ratio was calculated in the following way. First, the average temperature over years 401–500 was calculated at each grid point for both the global warming and unperturbed variability experiments. Then the CO₂ induced warming was calculated at each grid point by taking the difference between these time-averaged values. This procedure was carried out for both control and fixed H₂O cases and a ratio was taken at each grid point. Regions where the ratio exceeds 4 are shaded. In the fixed H₂O global warming experiment, cooling actually occurred in a small region of the circumpolar ocean near 120°W. For the purposes of this contour plot, the ratio of the warming in this region was assumed to be greater than 6. (b) The geographical distribution of the ratio (control/fixed H₂O) of the standard deviation of annual-mean surface temperature. Regions where the ratio exceeds 1.3 are shaded.

non. This drastically reduces surface temperature variability in this region.

In section 5, we compared the impact of water vapor feedback on internally generated anomalies and global warming by comparing the ratio of standard deviation of surface temperature to the ratio of global warming. However, the results of this section make it clear that both of these ratios are affected by other feedback mechanisms. Moreover, the magnitude and sign of the other feedbacks may not be the same in the unperturbed variability and global warming contexts. Thus the ratio of the warmings could be larger than the ratio of the standard deviations because the net strength of the other feedbacks is more positive in the global warming con-

text. Although this is unlikely to account for the large difference in the ratios, it is nevertheless desirable to verify that the difference in the strength of water vapor feedback is mainly responsible for the disparity in the ratios, and that our explanation for the larger impact of water vapor feedback on greenhouse-gas-induced climate change presented in section 5 is therefore robust. A detailed analysis of all feedback mechanisms in the unperturbed variability experiments is a complicated issue that is beyond the scope of this paper. However, it is simple to estimate the radiative strength of water vapor feedback in unperturbed variability using the offline version of the radiative transfer code. Such a calculation facilitates a quantitative comparison of the ra-

diative impact of water vapor feedback in natural variability and global warming contexts isolated from the effects of the other feedbacks. To perform this task, we first regressed annual-mean water vapor time series of the control unperturbed variability experiment at every grid point and vertical level with annual-mean, global-mean surface temperature. These regressions provide a measure of the changes in water vapor that occur throughout the model atmosphere for a global-mean surface temperature anomaly of 1°C . These water vapor anomalies were then imposed on the off-line radiative transfer code and the resulting global-mean decrease in outgoing longwave radiation was calculated. This decrease, when divided by λ_o , gives the gain factor associated with water vapor feedback in natural variability. Using this method, we calculated a gain factor of 0.18 for the longwave effects of water vapor feedback. The global warming counterpart to this gain factor has a value of 0.33 (gain factor listed in Table 2 for water vapor minus the gain factor associated with the short-wave effects of water vapor). This calculation confirms that water vapor feedback is nearly twice as effective in the global warming context, whatever the magnitude and sign of the other feedbacks may be.

7. Conclusions

a. Summary

Here we summarize the picture of water vapor feedback that emerges from our experiments. In section 4, we showed that the control model has more internally generated surface temperature variability on all spatial scales and timescales than its fixed H_2O counterpart. Thus water vapor feedback is positive in the context of the model's unperturbed variability. However, the control/fixed H_2O ratio of standard deviation of surface temperature increases as spatial scales increase. This implies that water vapor feedback is more effective the larger the spatial scale. The degree to which a surface temperature anomaly of a given spatial scale penetrates the troposphere is a critical factor in explaining the spatial-scale dependence of its associated water vapor feedback: global-mean anomalies penetrate more deeply into the troposphere than local ones. Since relative humidity does not change very much as surface temperature fluctuates, this implies a stronger relationship between tropospheric absolute humidity and surface temperature on large scales than small. Water vapor feedback may also become less important at smaller scales because much of the damping of surface–troposphere anomalies is accomplished by horizontal advection of sensible and latent heat, rather than radiative processes, diluting the effects of water vapor feedback.

In section 5, we confirmed that the model's water vapor feedback is also positive in the context of global warming. The equilibrium global warming at the surface due to a doubling of CO_2 in the control experiment was

3.38°C , while for the fixed H_2O case the warming was only 1.05°C . Thus the suppression of internally generated variability by removing a positive feedback also has the effect of reducing the climate sensitivity to an increase in greenhouse gases. However, we also noted that the ratio of equilibrium global warming (control/fixed H_2O) is significantly larger than the ratio of standard deviation of surface temperature in the unperturbed variability experiments at the global spatial scale. Thus the model's water vapor feedback is more effective in global warming than unperturbed variability. Like the explanation for the dependence of water vapor feedback on spatial scale, this difference is rooted in the discrepancy between the tropospheric distribution of the warming in the global warming experiment and the characteristic tropospheric structure of temperature anomalies in the unperturbed variability experiment. In the global warming case, the temperature increase extends throughout the troposphere, whereas in the unperturbed variability case, a typical surface temperature anomaly tends to decrease in amplitude with height. At the same time, simulated surface temperature changes tend to induce very little change in tropospheric relative humidity in both unperturbed variability and global warming cases. For global warming and internally generated temperature anomalies of identical magnitude, there is therefore a smaller change in atmospheric humidity, and hence absorptivity, associated with the internally generated anomaly.

In this section, we also shed light on the reason why internally generated, global-mean temperature anomalies do not penetrate as effectively into the troposphere as the warming induced by a doubling of CO_2 . We showed that when CO_2 increases, the lower-tropospheric warming at a given location is associated with a very similar warming aloft. Thus the global-mean warming is uniform throughout the troposphere as well. Conversely, the regions contributing most to internally generated, global-mean variability in the lower troposphere do not correspond to the regions that contribute most to internally generated, global-mean variability in the mid- to upper troposphere. Temperature fluctuations in the regions that dominate the mid- and upper-tropospheric global-mean variability are most likely only weakly related to temperature fluctuations in the distant regions that dominate the global-mean variability in the lower troposphere. The regression between global-mean tropospheric temperature and surface temperature therefore decreases with height. This points to a difference—of fundamental importance for water vapor feedback—between internally generated, global-mean temperature variability and the global-scale temperature anomaly that results from an increase in CO_2 ; internally generated, global-mean temperature anomalies at any level of the troposphere are a superposition of many modes of variability, whose individual impact is not geographically uniform, and that may not affect all parts of the

troposphere equally. Global warming, on the other hand, is the response to a steady, globally uniform forcing.

Since water vapor feedback has a different impact on internally generated and greenhouse-gas-forced temperature anomalies, it is not straightforward to estimate the climate sensitivity to a doubling of CO_2 based on an analysis of internally generated variability alone. This fact has implications for previous studies. For example, Wigley and Raper (1990) examined low-frequency variability in stochastically forced energy balance models of various sensitivities to assess the probability that the warming trend in global-mean temperature observed over the past 100 yr is internally generated. However, their energy-balance model has the same sensitivity to an increase in greenhouse gases as it does to the low-frequency stochastic forcings they imposed to mimic internally generated, global-mean temperature fluctuations. Our study indicates that this assumption does not apply to the real climate.

The results of sections 4 and 5 are consistent with the original hypothesis that, for the purposes of quantifying the effects of water vapor feedback on surface temperature, water vapor in the model atmosphere is essentially controlled by the Clausius–Clapeyron equation. Whether the context is unperturbed variability or global warming, a surface temperature change is associated with very little change in relative humidity aloft and the atmospheric water vapor content tends to remain proportional to the water vapor storage capacity of the atmosphere. Given this observation, what controls the strength of water vapor feedback is the degree to which a surface temperature anomaly penetrates the troposphere. The more it penetrates, the stronger the water vapor feedback. In the real climate, relative humidity may deviate from constant values to a greater degree than in the model as surface temperature fluctuates (Sun and Held 1996). The vertical structure of a surface–troposphere temperature anomaly is nevertheless a useful starting point from which to gauge the expected strength of its associated water vapor feedback, whether the context is a numerical model or the real climate. This conclusion is consistent with the work of Bony et al. (1995), who analyzed the relationships between tropospheric water vapor, outgoing longwave radiation, and surface temperature in satellite data and output from model experiments in which CO_2 was doubled and the solar constant was increased by 2%. They found that the relationships among these three variables were different depending on whether the type of climate variation under consideration was seasonal and interannual variability, or climate change due to some external forcing. They attributed these differences to the fact that the tropospheric lapse rate behaves differently in the various cases.

In section 6, we examined the interaction between water vapor feedback and other feedback mechanisms. We showed that other feedbacks alter the impact of water vapor feedback. To quantify this effect, we calculated

the radiative impacts of all feedbacks in the CO_2 -induced warming of both models using an off-line version of the model's radiative transfer code. We showed that the surface albedo and cloud feedbacks are positive in both the control and fixed H_2O cases. They therefore act to enhance the apparent impact of water vapor feedback. This interaction among feedback mechanisms explains why our rather large estimate of water vapor feedback's impact on global warming is not in contradiction to previous estimates, which are based on the assumption that water vapor feedback is the only feedback operating and are therefore smaller. Our estimates of the impact of water vapor feedback on unperturbed temperature variability are also affected by the other feedbacks. We therefore verified that it is the difference in water vapor feedback, rather than the other feedbacks, that is the main reason why the control/fixed H_2O ratio of the warming is so much larger than the control/fixed H_2O ratio of unperturbed variability. Using the off-line radiation code, we demonstrated that the changes in water vapor associated with a global mean surface temperature anomaly reduce the radiative damping of surface temperature about half as much as the increase in water vapor associated with a CO_2 -induced global warming anomaly of the same magnitude. This was additional confirmation that water vapor feedback is much stronger in the global warming context. Since the other feedbacks affect the apparent impact of water vapor feedback and may not be perfectly simulated by this model, our estimates of the effect of water vapor feedback should not be taken too literally. Our main conclusions regarding the spatial-scale dependence of water vapor feedback and its differing impact on unperturbed variability and global warming are meant to be robust in a qualitative sense.

b. Discussion: Comparison of observed and modeled variability

In this final section, we place the model's water vapor feedback in the context of the real climate. We assess the realism of the model's water vapor feedback by comparing the surface air temperature variability in the simulations with and without water vapor feedback to the observed surface temperature record. This comparison will allow us to address the following question: Is the model's water vapor feedback necessary to simulate the observed levels of variability?

Figure 8 shows the geographical distribution of standard deviation of annual-mean surface air temperature ($^{\circ}\text{C}$) for three cases: the control unperturbed variability experiment, the observed, and the fixed H_2O unperturbed variability experiment. Although the calculations shown in this figure are based on surface air temperature, rather than surface temperature itself, as elsewhere in this study, the two variables are very tightly linked everywhere on the globe on timescales longer than a few years. For example, analyzing a very similar model,

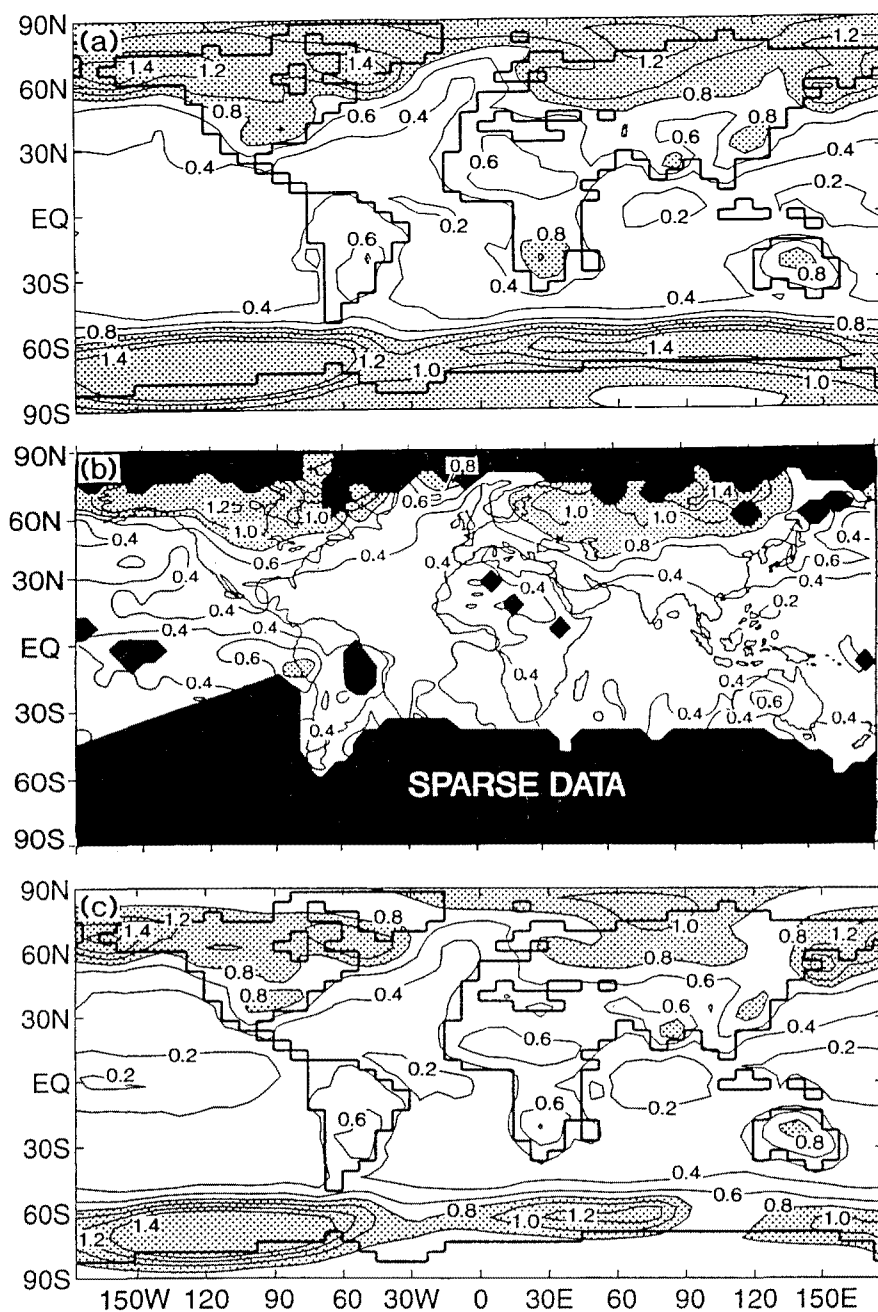


FIG. 8. The geographical distribution of standard deviation of annual-mean surface air temperature ($^{\circ}\text{C}$) for three cases. (a) The control unperturbed variability experiment. (b) The observed standard deviation, as calculated from a 110-yr time series compiled by Jones and Wigley (1991). The standard deviations were calculated by Stouffer et al. (1994), who used the following method. They obtained annual-mean temperature values at those grid points, spaced 5° apart, where at least 10 monthly mean values are available. Standard deviations were then calculated at those grid points where at least 33 annual-mean values are available. (c) The fixed H_2O unperturbed variability experiment.

Manabe and Stouffer (1996) showed that the average spectrum of local sea surface temperature is nearly identical to the average spectrum of local surface air temperature at timescales longer than about two years. The

same would be true at land points at even shorter time-scales since the model's land surface has no heat capacity. Thus for the purposes of measuring the low-frequency variability at or near the surface, the two

variables may be used as surrogates for one another. The use of surface air temperature here was dictated by the lack of availability of surface temperature data, particularly over land, where surface air temperature is more commonly measured.

In the mid- to high latitudes of the Northern Hemisphere, both the fixed H_2O and control integrations do a reasonable job of simulating the observed variability. For example, in Fig. 8, the 0.8°C contours of the fixed H_2O and control cases over the North American and Eurasian continents agree equally well with the observed, although they differ somewhat from one another. At the same time, the 0.4°C contours in the North Atlantic agree very well among all three cases. The control experiment shows much more variability in the high latitudes of the Southern Hemisphere than its fixed H_2O counterpart; unfortunately, the observed data necessary to identify the more realistic simulation do not exist in this region. In the Tropics, the standard deviations over land from both experiments agree reasonably well with the corresponding observed standard deviations, so that both models do a respectable job of simulating the observed variability in these regions. In the equatorial Pacific, the standard deviation of surface air temperature in both model configurations is noticeably less than the observed. This is because the model's ENSO-like phenomenon is weaker than observed (Knutson and Manabe 1997). However, this disagreement with observations is much more apparent in the fixed H_2O case, which actually shows a minimum in standard deviation in this region. In addition, the standard deviation in the fixed H_2O case is less than 0.2°C in more areas than either the observed or the control case in the other tropical zones, although the difference is not large.

With the exception of the equatorial Pacific and to a lesser extent the other tropical ocean regions, it cannot be claimed that the control experiment is more realistic than the fixed H_2O ; water vapor feedback simply does not have enough impact on local temperature variability to identify one of the two experiments as the more realistic simulation. This leaves open the question of whether water vapor feedback is necessary to reproduce observed levels of variability. However, the picture should be different if global-mean temperature variability is considered. In section 4, we established that water vapor feedback is more effective on larger spatial scales than small. Therefore, an examination of global-rather than local-scale anomalies ought to result in a larger difference between the two unperturbed variability experiments, which will hopefully establish one of the models as the more realistic one. In Fig. 9, we plot the time series of global-mean, annual-mean surface air temperature for four cases. Figure 9a shows the observed time series over the past 110 yr. This time series may be regarded as the observed unperturbed variability, assuming that the warming trend it contains is an internally generated fluctuation of the climate system. Figure 9b shows the same time series with the warming

trend removed. This time series may be regarded as the observed unperturbed variability, assuming that the warming trend of the top panel is entirely due to external forcing. Figures 9c and 9d show the last 400 yr of the control and fixed H_2O time series.

The standard deviations for each time series are shown in their respective panels. With a standard deviation of 0.211°C , the undetrended observed time series exhibits by far the most variability. The large standard deviation is almost entirely due to the warming trend. The detrended observed time series has less variability, with a standard deviation of 0.128°C . The control time series has approximately the same standard deviation as the detrended observed time series (0.127°C), while the fixed H_2O time series has the least variability of all, with a standard deviation of 0.083°C . The relative magnitude of the standard deviations of the two time series from the unperturbed variability experiments is consistent with the results presented in section 4: The presence of water vapor feedback enhances significantly global-scale surface air temperature variability.

We begin the discussion of these results by assuming that the observed warming trend is an internally generated fluctuation and that the topmost panel therefore represents unperturbed variability of surface temperature. Given this assumption, it is clear from both visual inspection of the fixed H_2O and undetrended observed time series and a comparison of their standard deviations that the model without water vapor feedback does not have enough internally generated variability to reproduce the sort of temperature fluctuation seen in the observed undetrended time series. At the same time, the standard deviation of the fixed H_2O time series is also substantially less than that of observed time series with the warming trend removed. Even after minimizing the standard deviation of the observed time series by making the opposite assumption that the warming trend is externally forced, the fixed H_2O model still fails to reproduce the observed unperturbed variability. Therefore, no matter whether we assume the observed trend is internally generated or externally forced, we are unable to simulate the observed global-mean variability without water vapor feedback.

We may make a similar comparison between the observed variability and the control time series. Assuming, again, that the observed warming trend of Fig. 9a is an internally generated fluctuation, the control run also fails to reproduce the observed variability. Not only is the standard deviation of the observed, undetrended time series nearly 70% greater than that of the control case, but nowhere in the control time series is there such a large and sustained trend as is seen in Fig. 9a. This result is consistent with the work of Stouffer et al. (1994), who assessed the probability that a very similar model could reproduce the observed century-scale warming trend without any external forcing. They found that for intervals longer than about 60 yr, no trends as large as the observed trend ($0.5^\circ\text{C century}^{-1}$) can be found in a 1000-yr time series of surface air temperature.

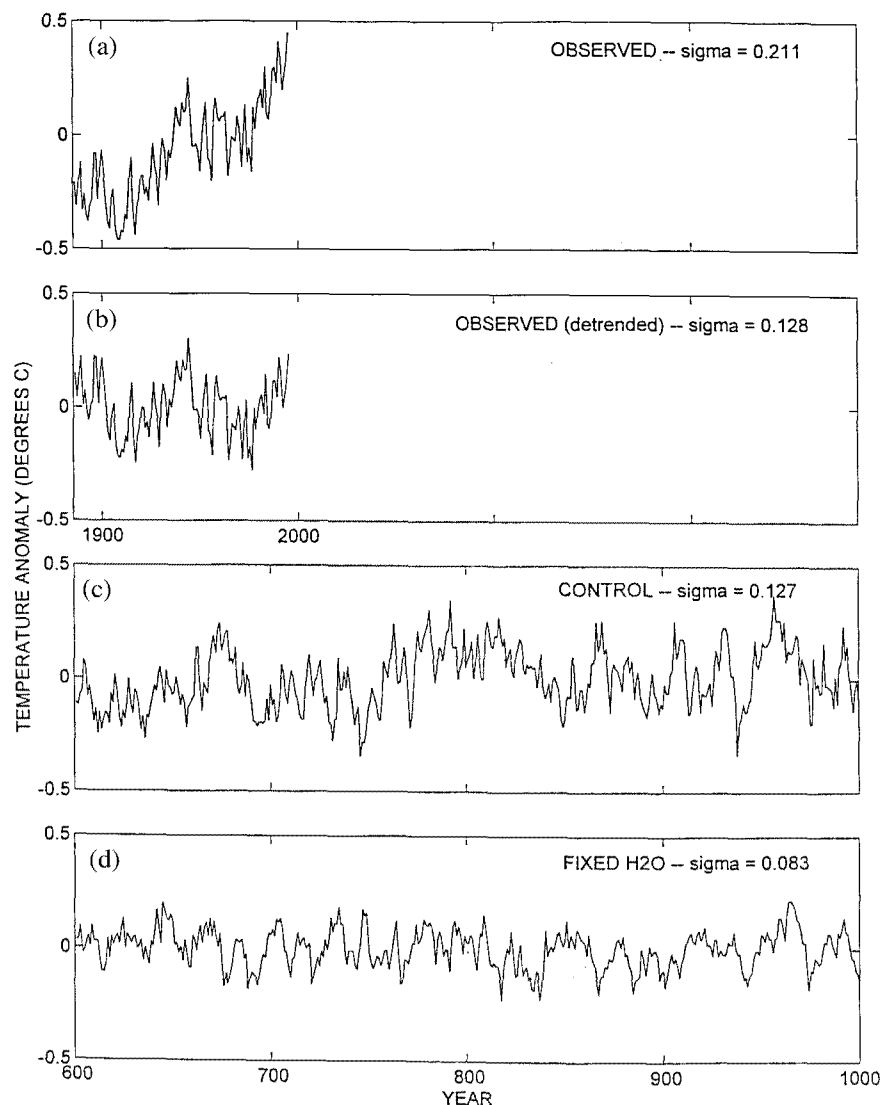


FIG. 9. The time series of global-mean, annual-mean, surface air temperature for four cases. (a) The observed time series over the past 110 yr. (b) The same time series as in (a) with the warming trend removed. The trend was assumed to be linear. (c), (d) The last 400 yr of the control and fixed H_2O time series. The standard deviations for each time series are shown in their respective panels.

Therefore, even with water vapor feedback included, the model still cannot reproduce a fluctuation of the type shown in the topmost panel. The other alternative is to assume the warming is externally forced. In this case, the standard deviations of the control and observed detrended time series agree quite well (although their near-perfect agreement is certainly fortuitous). While a comparison with the observed record reveals definitively that we are unable to simulate the observed levels of variability without water vapor feedback, the model with water vapor feedback has about the right amount of global-scale variability if the observed warming trend is assumed to arise from external forcing.

Acknowledgments. The authors wish to thank Isaac Held, Jerry Mahlman, Brian Soden, and Ron Stouffer for many helpful discussions as well as constructive criticism of the manuscript before it was released for publication. In addition, the article was greatly improved as a result of the comments of two reviewers, Graeme Stephens and Simon Tett. Alex Hall was supported by a NASA Earth System Science Fellowship while this research was being carried out. Observed global-mean surface temperature data were compiled by the Climate Research Unit of the University of East Anglia (United Kingdom) and obtained from their Web site: <http://www.cru.uea.ac.uk:80/cru/data/temperature.htm>.

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From: Ross McKittrick <ross.mckittrick@gmail.com>
Sent: Wednesday, May 21, 2025 10:33 AM
To: Steven Koonin
Cc: Judith Curry; John Christy; Roy Spencer; Travis Fisher
Subject: Re: ch 4 revisions

I found the part about lapse rate interacting with water vapor hard to follow. How is this rewording of the two paragraphs:

By itself, the equilibrium warming effect of a doubling of atmospheric CO₂ is slightly more than 1°C (Soden and Held 2006). The large values of ECS arise from positive feedbacks that amplify the CO₂ warming. Water vapor feedback is positive: a warmer atmosphere may have more water vapor, which itself is a powerful greenhouse gas. Warmer temperatures also result in less snow and sea ice cover, allowing the Earth to absorb more of the sun's radiation. Some simple estimates of these feedbacks increase the ECS to around 2°C (Sherwood et al., 2020).

Higher values of ECS arise primarily from positive cloud feedbacks whose magnitude, and even sign, are highly uncertain. Elements of cloud feedback include changes in the latitudinal distribution of clouds, changes in the distribution of cloud height (changes in low versus high clouds), changes to the phase of clouds (ice versus liquid), changes in cloud particle size (associated with changes in concentration and/or composition of aerosol particles), changes in the precipitation efficiency of clouds, and even changes in how clouds are distributed over the daily solar cycle (Curry and Webster, 1999). It is difficult for climate models to simulate any of these processes correctly owing to their small scale, let alone predict how they will change in the future. Further, cloud processes modulate the magnitudes of the water vapor, lapse rate, and the surface albedo feedbacks.

On Wed, May 21, 2025 at 10:20 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Easiest for me to think about it as follows:

Forcing from CO₂ is $(5.4 \text{ W/m}^2) \ln(C/C_0)$. For doubling CO₂, the $\ln$ is 0.7, giving a forcing of 3.8 W/m²

The Black Body (Boltzmann) feedback parameter for all models is about -3.3 (W/m²)/K, as can be directly computed from the SB law.. So the direct temperature rise is 3.8/3.3 or about 1.2 K.

Feedbacks then come on top of this, allegedly to double or triple the sensitivity

From: Ross McKittrick <ross.mckittrick@gmail.com>
Sent: Wednesday, May 21, 2025 10:07 AM
To: Judith Curry <curry.judith@gmail.com>
Cc: Steve Koonin <steven.koonin@gmail.com>; John Christy <climateman60@gmail.com>; Roy Spencer

<roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>

Subject: Re: ch 4 revisions

Hall and Manabe 1997 (attached, Fig 3) is the one I use to make the point about 1C direct effect from CO2 doubling. Yesterday we were debating the forcing amount from CO2 doubling.

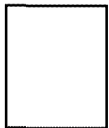
On Wed, May 21, 2025 at 10:03 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

What is the citation indicated as a superscript 33?

On Wed, May 21, 2025 at 9:31 AM Judith Curry <curry.judith@gmail.com> wrote:

attached, added text in red

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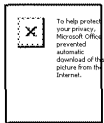
Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
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<http://www.cfanclimate.net>

From: Ross McKittrick <ross.mckitrick@gmail.com>
Sent: Wednesday, May 21, 2025 10:04 AM
To: Judith Curry
Cc: Steve Koonin; John Christy; Roy Spencer; Travis Fisher
Subject: Re: ch 4 revisions

What is the citation indicated as a superscript 33?

On Wed, May 21, 2025 at 9:31 AM Judith Curry <curry.judith@gmail.com> wrote:
attached, added text in red

--



Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
<http://www.cfanclimate.net>

From: Judith Curry [curry.judith@gmail.com]
Sent: 5/1/2025 6:42:07 PM
To: Ross McKittrick [ross.mckittrick@gmail.com]
CC: Steven Koonin [steven.koonin@gmail.com]; John Christy [climatemanager60@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]
Subject: Re: Ch 5 ECS
Attachments: 5 Climate Sensitivity.May1.Merged JCurry.docx

Hi Ross, I've made another round of revisions, mainly suggesting some text be removed.
(totally agree group statement isn't needed)

This chapter may require a lot of back and forth, SK may want to chime in

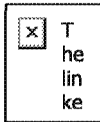
On Thu, May 1, 2025 at 11:14 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

Hi Judy

I posted (& attached) a version of your ECS chapter that cleans up the formatting and merges back in some of the text I had included previously that I think helps it connect to the IAM discussion. I added a couple of comments in red font. I'm reluctant to include a group statement at the end about a likely ECS range. Also I converted the superscripts to insertions where the (name, date) citation will need to be inserted.

Ross

--



The
link

Judith Curry, President
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5 Measuring Climate Sensitivity to CO₂ Forcing

5.1 Introduction

The magnitude of the sensitivity of Earth's climate to increasing concentrations of CO₂ is at the heart of the scientific debate on anthropogenic climate change, and also the public debate on the appropriate policy response to increasing CO₂ in the atmosphere. Equilibrium Climate Sensitivity (ECS) refers to the expected amount of warming averaged over the Earth's surface in response to a doubling of CO₂, after all climate systems have had time to adjust. Some systems, like temperatures in the troposphere, adjust very rapidly. Others may take decades or even centuries, such as the deep ocean and the cryosphere. A related metric which is sometimes more helpful for analysis on shorter time scales is the Transient Climate Response (TCR) defined as the amount of warming after 70 years in which atmospheric CO₂ goes up by one percent annually.

In 1979 the Charney (1979) Report for the US National Academy of Sciences proposed that the most likely value for ECS was 3.0°C plus or minus 1.5°C. With only minor variations this range was adopted and reaffirmed by the IPCC until the most recent AR6. The ECS range between 1.5 and 4.5°C is characterized by the IPCC AR5 as the *likely* range (66 percent probability); the AR5 stated that ECS is *extremely unlikely* (95 percent probability) to be below 1.0°C and very unlikely (90 percent probability) to exceed 6.5°C. This range of ECS values has remained stubbornly wide, despite many individual studies claiming to narrow it. Most recently, the IPCC AR6 narrowed its assessment of the *likely* range of ECS to 2.5–4.0°C and the *very likely* range to be between 2.0 and 5.0°C. This narrowing of the range on the low end is disputed, as will be discussed below.

Uncertainties about ECS are highly consequential for policy making. As will be discussed in Chapter 13, economic models take the ECS value from climate science and use it to project the costs of CO₂ emissions. The traditional ECS value (3.0 °C) has typically yielded modest global social costs of CO₂ emissions, enough to justify some policy actions though mostly deferred to later in the century. If ECS is very high (4.5°C or above) aggressive immediate emission controls become more imperative, whereas values closer to 2.0°C have been shown to imply that no CO₂ emission controls are economically justifiable (Dayaratna et al. 2016, 2020). Obtaining a precise ECS estimate is therefore important for policy guidance. Obtaining a precise estimate is impossible, policy making needs to account for the uncertainty.

5.2 Model-based methods of computing climate sensitivity to GHGs

The ECS range has been obtained primarily by examining the behaviour of climate models, but since key components of models are under the control of modelers this is not dispositive of the actual climate's sensitivity. There are approximately three dozen computer climate models operated by research groups around the world (Cannon 2024). GCMs are valuable tools for understanding the climate system from a theoretical perspective. But the models have become so complex, often with 1 million or more lines of computer code (Brown-Steiner 2024), that it would be prohibitively expensive and time consuming for anyone to replicate the models' projections of climate change, let alone test the myriad model approximations embedded in the computer codes; a climate model typically takes hundreds of experts many years to develop (McSweeney and Hausfather 2018). As a result, these models are published in the scientific literature with little to no independent evaluation (Pirtle et al 2010). Climate modeling thus stands as an unusual class of scientific endeavor wherein researchers validating the scientific claims of others — a hallmark of science (National Academy of Science 2019)— becomes impractical, if not impossible.

In large-scale General Circulation Models (GCMs, aka climate models) ECS is not imposed as a direct parameter, instead it emerges from the behaviour of the underlying components of the model. Collections of parameterizations are often chosen to produce an expected value of climate sensitivity, particularly with regards to sub-grid-scale cloud processes. Otherwise plausible models and parameter selections have been discarded because of perceived conflict with this warming rate, or aversion to a model's climate sensitivity being outside an accepted range. For example, Mauritsen and Roeckner (2020) state the following regarding their Max Planck Institute climate model:

"We have documented how we tuned the MPI-ESM1.2 global climate model to match the instrumental record of warming; an endeavor which has clearly been successful. Due to the historical order of events, the choice was to do this practically by *targeting an ECS of about 3 K using cloud feedbacks*, [emphasis added] as opposed to tuning the aerosol forcing."

In other words, the modelers chose an ECS value of 3°C and then tuned the cloud parameterizations to match their intended result.

Direct warming from CO₂ doubling is only about 1°C (Hall and Manabe 1997); ~~the rest, to the extent more happens, arises due~~ higher values arise from climate feedbacks that are not explicitly resolved by the model but rely on parameterizations of physical processes ~~which are inherently more difficult to predict and model~~. Higher values of ECS arise primarily from positive cloud feedbacks. The magnitude, and even the sign, of cloud feedbacks is the greatest source of uncertainty. Elements of cloud feedback include changes in the latitudinal distribution of clouds, changes in the distribution of cloud height (changes in low versus high clouds), changes to the phase of clouds (ice versus liquid), changes in cloud particle size (associated with changes in concentration and/or composition of aerosol particles), changes in the precipitation efficiency of clouds, and even changes in how clouds are distributed over the daily solar cycle [source 35]. It is difficult for climate models to simulate any of these cloud processes correctly owing to their small scale, let alone predict how they will change in the future. Further, cloud processes modulate the magnitudes of the water vapor, lapse rate, and the surface albedo feedbacks [source 36].

ECS can be determined from climate model simulations by doubling the concentration of CO₂, allowing several centuries for the warming to equilibrate. To avoid the necessity of long simulations, "effective climate sensitivity" is commonly evaluated from a 150-year simulation in response to a sudden quadrupling of CO₂. The spread of ECS values from the CMIP5 climate models (used in the AR5) was 2.0–4.7°C; the spread has increased for the CMIP6 models (used in the AR6) to between 1.8 and 5.7°C [sources 37,38]. Far from the science being settled in relation to the response of the climate system to increasing greenhouse gas concentrations, insofar as it is represented by climate models, uncertainties appear to be growing. The main cause of the overall upward shift in ECS in CMIP6 relative to CMIP5 is a larger positive cloud feedback, driven by changes to the cloud parameterizations in many CMIP6 models.[source 39]

~~THIS ISN'T VERY RELEVANT.~~ While the models are often touted as being accurate representations of the "basic physics" governing the climate system, they still have problems with model "drift," in which the models slowly change temperature over centuries for no apparent reason (Grandey et al. 2023). The tendency to drift is adjusted for by climate modelers imposing the arbitrary assumption that Earth's climate system does not produce long-term climate change, unless caused by humans (Sen Gupta et al 2013). Suppressing all slow-moving warming and cooling in this way biases model-based research away from potential natural causes of climate change since it implies there can be no warming trends except in response to external forcing. In addition recent research suggests many

models do not even conserve energy (Irving 2021) — a violation of the First Law of Thermodynamics. The First Law holds that energy can be neither created nor destroyed; to the extent that climate models fail to conserve energy, it can spontaneously appear (or disappear) for no apparent reason, causing a fictitious temperature change. This is a particularly important consideration since global warming theory is first and foremost based upon tiny changes in the global energy balance assuming the First Law holds.

Because of concerns about model tuning and the high sensitivity to cloud parameterizations, the IPCC AR6 (2021) did not rely on climate model simulations in their assessment of climate sensitivity, relying on other methods in its assessment instead, chiefly a recent empirical estimate.

5.3 Data-driven methods of computing climate sensitivity to GHGs

Climate sensitivity can also be estimated from instrumental records of surface temperatures and ocean heat content, combined with estimates of how climate forcings (e.g., greenhouse gases, solar, volcanoes, aerosols) have changed in the past. [source 40] Using this information, a simple empirical model called an Energy Balance Model can be estimated. It requires estimating a feedback parameter which appears in the denominator of the resulting equation for ECS. NO EQUATIONS, whose uncertainties are highly amplified in the resulting ECS (Roe and Baker, 2007). A small amount of uncertainty about the number in the denominator of a fraction can lead to very large uncertainties in the magnitude of the fraction itself. Roe and Baker (2007) pointed out that for this reason uncertainties in climate feedbacks are “highly amplified” in the resulting ECS.

The accuracy of the data-driven methods depends on the quality of the input data. Assumptions are needed about ocean heat storage, and the ocean data is inadequate. The greatest source of uncertainty is the amount and composition of aerosol particles and their interactions with cloud radiative properties (the so-called aerosol indirect effect). Climate models exhibit warming in response to GHGs but cooling in response to aerosols (Schwartz et al. 2007). Observed 20th century warming can be shown to be consistent either with low ECS and low aerosol cooling or high ECS and high aerosol cooling. Since fossil fuel use adds both GHGs and aerosols to the atmosphere, both effects need to be estimated to isolate the warming effect of CO₂. Over time, the IPCC’s estimate of the cooling effect of aerosols has declined (Lewis 2022).

Paleoclimate proxies are also used to evaluate the sensitivity of past climates, by comparing paleoclimate changes in the Earth’s temperatures to estimates of changes in forcings. The two most informative periods are the last glacial maximum (around 20,000 years ago), which was about 3–7°C colder than today, and a mid-Pliocene period (roughly three million years ago), which was 1–3°C warmer than today. [source 41] The limits on cooling during the last glacial maximum give the best single evidence that high values of climate sensitivity are unlikely. However, paleoclimate estimates are associated with very large uncertainties in the estimated temperatures and forcings. Further, estimates of climate sensitivity based on past climate states may not be representative of the current state of the climate system.

A recurring theme in the climate literature is that ECS estimates based on historical data turn out to be smaller than ECS estimates inferred from climate models (Sherwood and Forest 2024). An early empirical estimate (Stern and Kaufmann 2000) was 1.6°C, though this predated development of the Energy Balance Model method. Figure 5.1 shows the point or best estimates from 17 subsequent studies all appearing in the peer-reviewed literature since 2012. The Charney range is shown for contrast. The average ECS point estimate in the post-2012 sample is 1.8°C. The highest estimate, from

Sherwood et al. (2020), is shown in red; it is the one that was highlighted by the IPCC AR6 and used to guide their assessment of the ECS range (Forster et al. 2021). The one adjacent to it, Lewis (2022), was published subsequent to the AR6 and presented an extensive critique of Sherwood et al. (2020).

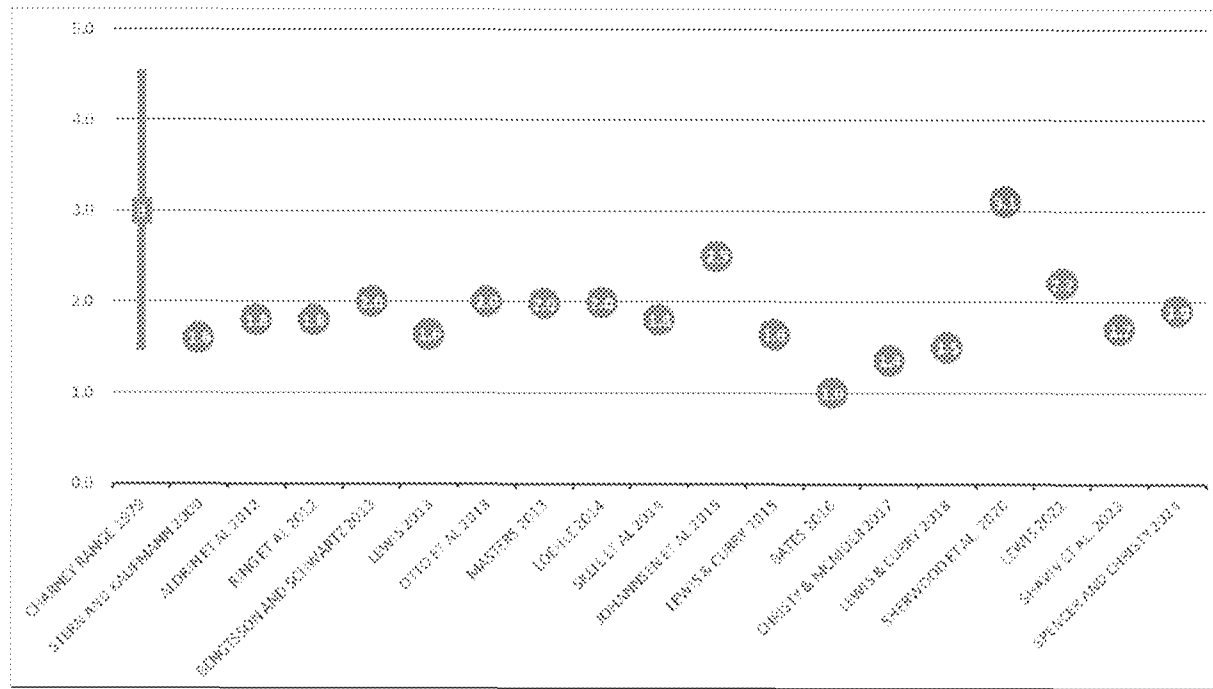


Figure 5.1: Empirical best estimates of ECS. Vertical axis: °C.

[Judy I reinserted this Figure as I think it is an important visual indicator that Lewis 2022 is not a one-off outlier.]

I don't this this is needed. Lewis (2022) is not a historical empirical method, but rather uses the same approach as Sherwood et al. and AR6 in combining historical, paleo and feedback approaches. I don't think that the older ones are useful because the data is pretty old, and methods outdated. Lewis (2022) is clearly within the the AR5 range, I don't think we need to resurrect the old stuff.

Key concerns raised by Lewis include methodological errors, outdated input values, and use of subjective versus objective Bayesian priors in the analysis. Lewis' analysis found that climate sensitivity is estimated to be much lower and better constrained than in the Sherwood et al. analysis – median 2.16°C (1.75–2.7°C in the 17–83 percent likely range), and 1.55–3.2°C in the 5–95 percent very likely range. Lewis' analysis implies that climate sensitivity is considerably more likely to be below 2°C than above 2.5°C. The IPCC AR6 estimated only a 5 percent probability that ECS was below 2.3°C, whereas Lewis (2022) estimated it to be over 50 percent. The most recent publications on the debate between Sherwood et al. and Lewis further defend their respective positions: Sherwood and Foster (2024) and Lewis (2025).

A recent argument, which the IPCC AR6 emphasized, is that data-driven ECS estimates might understate the future warming response to GHGs based on a so-called “pattern effect” (Forster et al 2021). The tropical Pacific is believed to be highly influential on the overall efficiency with which the

Earth's climate radiates heat to space, but in some regions heat is more efficiently removed from the climate system than from others. If in a warming climate there is a weakening of the west-to-east temperature gradient in the tropical Pacific the result would be a concentration of warming in a region where heat is less efficiently removed, raising the ECS of the Earth's climate system. Most climate models simulate that rising GHGs will weaken the east-west temperature gradient, which led the IPCC in the AR6 to conclude that data-driven ECS estimates understated the *future* ECS value.

However, Seager et al. (2019) pointed out that, contrary to models, the east-west temperature gradient has been strengthening rather than weakening over time. They further argued that the mechanism predicting otherwise in climate models was based on a faulty characterization of oceanic dynamics and there is no reason to expect the gradient to weaken. A similar argument was recently made by Lee et al. (2024), who concluded that "the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere"; in other words GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. Increased efficiency of atmospheric cooling implies, if anything, that the future ECS in a warming climate may be *lower* than current estimates.

5.5 Transient Climate Response

The Transient Climate Response (TCR) is of greater utility in providing an observational constraint on climate sensitivity. TCR is the amount of warming that would occur at the time when CO₂ doubles, having increased gradually by 1 percent each year over a period of 70 years. Relative to the ECS, observationally-determined values of TCR avoid the problems of uncertainties in ocean heat uptake and the fuzzy boundary in defining equilibrium arising from a range of timescales for the longer-term feedback processes (e.g., ice sheets). TCR is more generally related to peak warming and better constrained by historical warming, than ECS. The IPCC AR6 judged the *very likely* range of TCR to be 1.2–2.4°C. **[source 47]** In contrast to ECS, the upper bound of the TCR is more tightly constrained. For comparison, the TCR values determined by Lewis (2023) is 1.25 to 2.0°C, showing much better agreement with the AR6 values than was seen in a comparison of the ECS values.

A related but more flexible parameter is the Transient Response to cumulative carbon Emissions, or TCRE, which relates global temperature change to the cumulative emissions. TCRE is based upon a linear relationship between global average temperature and cumulative emissions, which holds for cumulative emissions of up to 2 teratons of carbon. For a given value of TCRE, we can calculate the estimated amount of warming expected over a future period in response to scenarios of cumulative carbon emission. The IPCC AR6 provides a *very likely* range for TCRE of 1.0–2.3°C, with a median value of 1.6°C.⁴⁸

As will be discussed in Chapter 6 a real-world ECS below the model average is supported by studies which show climate models on average estimate too much warming at the surface and in the troposphere compared to observations over the past 50 years. Also it aligns with evidence from consistent fingerprinting (Section 7) that model responses to GHGs need to be scaled down quite a bit to align with observed trends.

5.6 Summary

In the past 5 years, there is a growing realization that climate models are not fit for the purpose of determining the sensitivity of the climate to increasing CO₂ (ECS), owing to the dependence of this sensitivity on poorly resolved processes related to clouds and water vapor.

Data-driven approaches using historical data and paleoclimate reconstructions are now regarded as more reliable for determining ECS, but their reliability is diminished by data inadequacies. The IPCC AR6 upper bound for the *likely* range of ECS is 4.0°C, lower than the AR5 value of 4.5°C. This lowering of the upper bound seems well justified by the paleoclimatic estimates of the ECS. The IPCC AR6 lower bound for the *likely* range of ECS is 2.5°C, substantially higher than the AR5 value of 1.5°C. This raising of the lower bound of the likely range of ECS has received a substantial challenge from the analysis of Lewis (2022, 2025) that finds the lower bound of the likely range to be 1.75°C with a median value of 2.16°C. Other lines of evidence supporting a lower bound on the ECS range below the IPCC AR6 value are discussed in Chapters 6 and 7.

Estimates of the transient climate response (TCR; TCRE) are more tightly constrained on the upper bound than the ECS.

[Judy I took out the assessed value statement since I don't think we need to generate one and I wouldn't know how to do it] AGREED

Mauritsen, T., & Roeckner, E. (2020). Tuning the MPI-ESM1.2 global climate model to improve the match with instrumental record warming by lowering its climate sensitivity. *Journal of Advances in Modeling Earth Systems* 12, e2019MS002037; <https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019MS002037>

Zelinka, M. D., Myers, T. A., McCoy, D. T., Po-Chedley, S., Caldwell, P. M., Ceppi, P., et al. (2020). Causes of higher climate sensitivity in CMIP6 models. *Geophysical Research Letters*, 47, e2019GL085782. <https://doi.org/10.1029/2019GL085782>

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Steve

Now that we know a little more, we can mention that this is our preliminary report and that as public review ensues there are sure to be additions and alterations as we prepare a final report.

John C.

John Christy
Director, Earth System Science Center
Professor, Atmos and Earth Science
Alabama State Climatologist
The University of Alabama in Huntsville
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To join the line, dial 833-630-2129 and enter the guest code: 2403918#

I look forward to the discussion!

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Sent: Thursday, May 8, 2025 2:27 PM

To: Judith Curry <curry.judith@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Steven Koonin <steven.koonin@googlemail.com>

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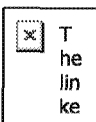
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From: Ross McKittrick <ross.mckitrick@gmail.com>
Sent: Friday, May 9, 2025 1:48 PM
To: Judith Curry
Cc: Roy Spencer; Steven Koonin; Travis Fisher; John Christy
Subject: Re: Ch 7 attribution
Attachments: 0.Intro.May9.[RM].docx

I'd like to suggest we aim for a very brief intro. We don't need to say it's a preliminary report or that it will be subject to comment and revision because we are also saying (rightly) that we aren't involved in the EPA process and we don't know what they'll do with it. Secretary Wright has indicated verbally he'd like a larger work product later on, but we don't know what form it will take, and to be honest once he sees it he may decide this report says everything that needs to be said.
So here's a suggested revision that goes the de minimis route.

On Fri, May 9, 2025 at 9:08 AM Judith Curry <curry.judith@gmail.com> wrote:
I agree that we can leave this statement out. Our list of references will stand on its own, and we start from the IPCC assessment reports which summarize a large number of papers

On Fri, May 9, 2025 at 2:41 AM Roy Spencer <roywspencer@hotmail.com> wrote:
Steve's intro is pretty good.

I have a little concern over the following:

"Nor have we attempted to survey entire literatures related to the topics covered. The scientific and technical material herein only samples vast literature on climate change but is, we believe, more than sufficient to establish our conclusions."

In my experience, the overwhelming majority of the literature simply assumes climate change is 100% human-caused, dangerous, and demands regulatory action. It doesn't actually demonstrate it.

Or, due to the complexity of the subject the literature deals with minutia that isn't meant to conclude any of that...only to improve our understanding of tiny pieces of the climate change puzzle.

My concern is that someone reading these sentences might conclude, Well, these (few) authors didn't really take the whole body of literature seriously.

Is there a way to rephrase? Or, maybe there's no easy way to address my concern.

-Roy

From: Steven Koonin <steven.koonin@gmail.com>
Sent: Thursday, May 8, 2025 4:38 PM
To: 'Travis Fisher' <travis.scott.fisher@gmail.com>; 'Roy Spencer' <roywspencer@hotmail.com>
Cc: 'Judith Curry' <curry.judith@gmail.com>; 'Ross McKittrick' <ross.mckitrick@gmail.com>; 'John Christy'

<climateman60@gmail.com>

Subject: RE: Ch 7 attribution

There is a draft (really just a start) of a joint intro in the 0.Intro.May1 file in the "00.Report Draft" folder (also attached). Y'all should have a look and comment/edit as you see fit.

SEK

From: Travis Fisher <travis.scott.fisher@gmail.com>

Sent: Thursday, May 8, 2025 5:17 PM

To: Roy Spencer <roywspencer@hotmail.com>

Cc: Judith Curry <curry.judith@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Steven Koonin <steven.koonin@gmail.com>; John Christy <climateman60@gmail.com>

Subject: Re: Ch 7 attribution

Apologies for the late start -- it's par for the course around here, unfortunately.

As we discussed, I'll coordinate with the Office of Public Affairs (the Sec. Wright team) and the other agencies involved. I'll also work with the Secretary on a draft of his cover letter.

Based on the call, it sounds like the Secretary wants a joint introduction or cover letter from the five of you. I'll defer to you all on whether/how you want to proceed with that, but please let me know if you want any help.

There are two other items I wanted to follow up on:

1) My former RA from Cato (Josh Loucks) will join the DOE team this coming Monday, and I'll ask for his help in formatting and finalizing the documents. Would you all flag for me when you think a given chapter is ready to be formatted?

2) There is a data visualization wizard on the political team here who can help with any charts or graphs that you want to rework. Please start thinking about which parts of the report you all want to remake or polish instead of borrowing images from other publications. I could go either way on the question of using images or rebuilding graphs -- I just want you to know we've identified someone on the team here who can help with that type of work if we decide to do it.

My only new thought on external review is that we could send specific chapters to specific reviewers without informing them about the entirety of the project. I'll leave it up to you all to identify the right reviewers and engage them as necessary. That could make the work more doable from the reviewer's point of view and perhaps less likely to leak.

Finally, it sounds like the Secretary supports labeling this version "interim" (or similar) and retaining this same team for a final version, in which you all would address any substantive comments directed at the interim report.

On Thu, May 8, 2025 at 4:09 PM Roy Spencer <roywspencer@hotmail.com> wrote:

Or we could enjoy this low fidelity classical music

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Judith Curry <curry.judith@gmail.com>

Date: 5/8/25 3:07 PM (GMT-06:00)

To: Ross McKittrick <ross.mckittrick@gmail.com>

Cc: Travis Fisher <travis.scott.fisher@gmail.com>, Roy Spencer <roywspencer@hotmail.com>,

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Subject: Re: Ch 7 attribution

if travis could initiate the meeting, we could chat while waiting for the secy

On Thu, May 8, 2025 at 1:05 PM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

on hold....

On Thu, May 8, 2025 at 3:48 PM Travis Fisher <travis.scott.fisher@gmail.com> wrote:

Yes, this meeting will be audio-only. I think future meetings will be video conferences.

On Thu, May 8, 2025 at 3:42 PM Roy Spencer <roywspencer@hotmail.com> wrote:

Is this meeting voice only?

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Travis Fisher <travis.scott.fisher@gmail.com>

Date: 5/8/25 2:19 PM (GMT-06:00)

To: Judith Curry <curry.judith@gmail.com>

Cc: Steven Koonin <steven.koonin@gmail.com>, Ross McKittrick <ross.mckittrick@gmail.com>,

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Introduction

This document originated in late March 2025 when Secretary Wright asked the authors to write a report on issues in climate science relevant for energy policymaking, with particular focus on the question of whether carbon dioxide emissions endanger the US public. We agreed to undertake the work on the condition that there would be no editorial oversight by the Secretary, the Department of Energy, or any other government personnel. This condition has been honored throughout the process and the writing team has worked with full independence.

The team writing this report was not involved in, nor briefed on, any Administration plans or processes related to a potential challenge to the 2009 EPA CO₂ Endangerment Finding. We were asked, however, to include some information related to the role of US motor vehicles in global climate change, since that is an issue of relevance to the Department of Energy.

The writing team is grateful to Secretary Wright for the opportunity to prepare this report and for his support for independent scientific inquiry.

From: Judith Curry [curry.judith@gmail.com]
Sent: 5/8/2025 7:02:50 PM
To: Steven Koonin [steven.koonin@gmail.com]
CC: Ross McKittrick [ross.mckittrick@gmail.com]; John Christy [climatemanager60@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]
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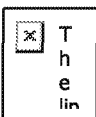
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From: Ross McKittrick <ross.mckittrick@gmail.com>
Sent: Monday, May 12, 2025 12:29 PM
To: Judith Curry
Cc: Steven Koonin; John Christy; Roy W. Spencer; Travis Fisher
Subject: Re: Ch 8 Extreme weather - new thread

Perhaps we could fill in a bit more detail about the categories in Table 12.12 in Section 7.4 where the discussion naturally belongs. Then in Ch 8 what about reducing 8.2 to something like this:

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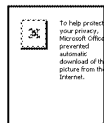
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 To help protect your privacy, Microsoft Office prevented automatic download of this picture from the Internet.

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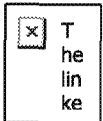
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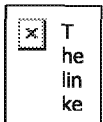
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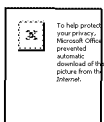
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From: John Christy [climateman60@gmail.com]
Sent: 5/12/2025 6:11:41 PM
To: Ross McKittrick [ross.mckittrick@gmail.com]
CC: Judith Curry [curry.judith@gmail.com]; Steve Koonin [steven.koonin@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]
Subject: Re: Ch 8 Extreme weather - new thread

Reading this thread from the 158th meridian is very interesting. I'm not sure where things are (will this be a new thread if it is chapter 7?)

I forgot to include the label for "Four Corners". Attached is correct plot.

I wrote the following but am not pleased with it as the conclusion to the Ext Precipitation section. It's rather weak, especially given the analysis Ross performed on the updated datasets:

"In most regions and perhaps all, it is our opinion that the very nature of the erratic and episodic character of extreme precipitation events renders the discovery of statistically significant changes, including a relationship to CO2 concentrations, a result yet to be achieved (McKittrick and Christy 2019)."

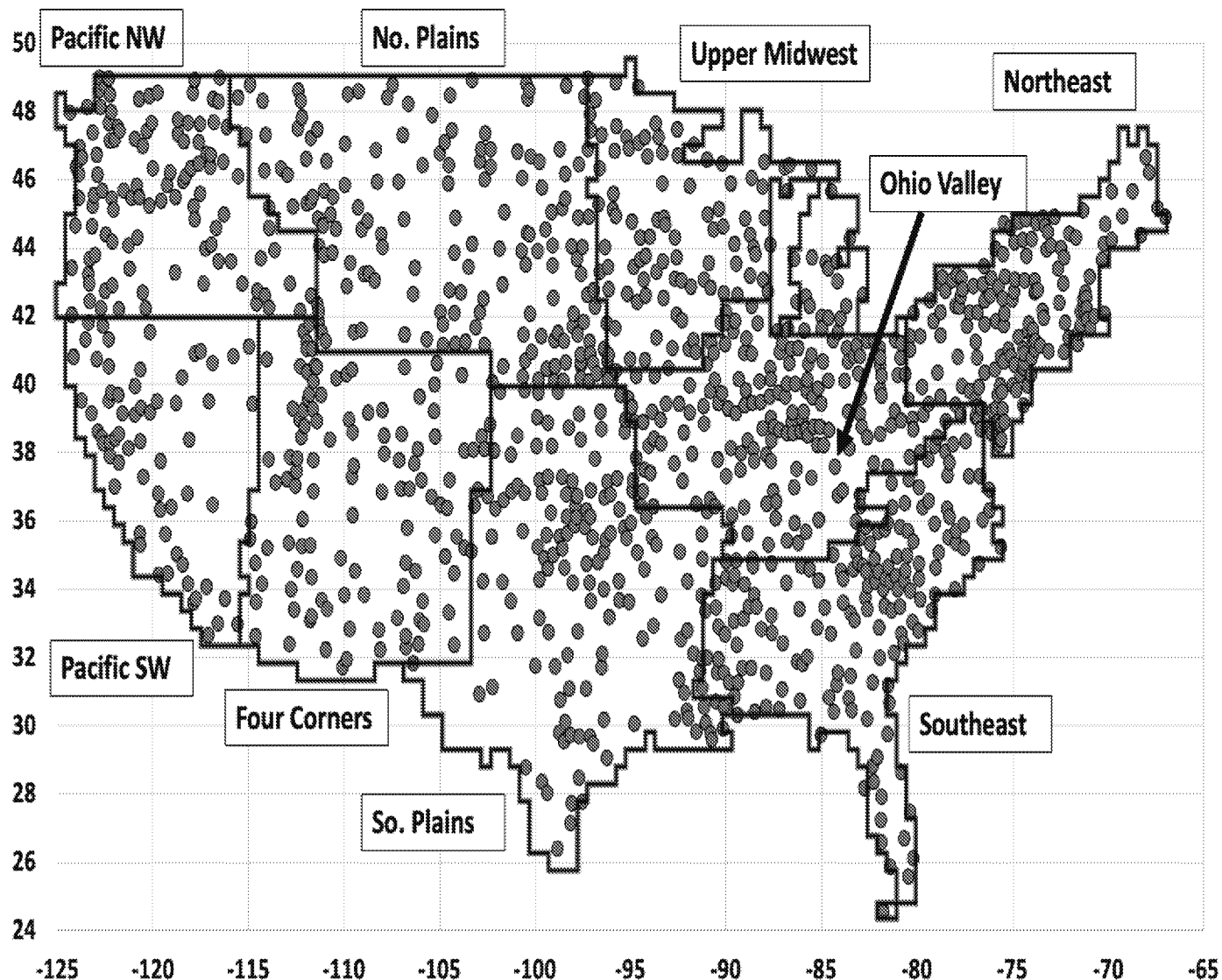
Try this?

Recognizing that the nature of extreme precipitation events is erratic and episodic, the updated CONUS-wide information provided here indicates that significant trends have not been detected (McKittrick and Christy 2019).

I will look at this again when I land in Huntsville Tuesday.

John C.

John Christy
Director, Earth System Science Center
Professor, Atmos and Earth Science
Alabama State Climatologist
The University of Alabama in Huntsville
climateman60@gmail.com



On May 12, 2025, at 12:00 PM, Ross McKittrick <ross.mckitrick@gmail.com> wrote:

That could work. The flow will be a bit choppy whichever order we have them in but maybe the attribution chapter should go at the end of Part II, i.e.

Part II: Climate response to greenhouse gas emissions

5 Measuring climate sensitivity to CO2 doubling

6 Models versus observations in recent past

7 Observed changes in extreme weather

8 Sea level rise

9 Uncertainties in analysis of attribution

On Mon, May 12, 2025 at 12:40 PM Judith Curry <curry.judith@gmail.com> wrote:

another suggestion is that i think it makes sense to switch the order of chapters 7 and 8 (detection before attribution)

On Mon, May 12, 2025 at 9:28 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

Perhaps we could fill in a bit more detail about the categories in Table 12.12 in Section 7.4 where the discussion naturally belongs. Then in Ch 8 what about reducing 8.2 to something like this:

8.2 Context: detection is not attribution

This chapter is concerned with detection of trends. Chapter 7 looked at causal attribution, with Section 7.4 specifically addressing extreme weather. If no trend is detected then clearly there is no basis for attribution. But even where a trend is observed attribution should not be assumed automatically to follow. Since there is considerable public interest in the question of whether humans are causing trends in extreme weather to get worse it is useful to recall that AR6 Table 12.12 indicates that, for 34 major weather event and impact types, detection of an anthropogenic signal is asserted with high confidence in only four of the 34 weather impact categories, and with medium confidence in a further four. The IPCC does not claim to have detected an anthropogenic signal in the remaining 26 categories. Of the four high confidence assertions, two are for changes in average temperatures (air and ocean), which are not measures of extreme weather. Also two of the four medium confidence assertions are related to ocean chemistry and are also not related to extreme weather. The IPCC does not assert a detectable human influence on many non-temperature weather features such as wind, precipitation, flooding, and drought.

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This is a good compromise, but technically the first column is detection and attribution

On Mon, May 12, 2025 at 8:33 AM Steven Koonin <steven.koonin@gmail.com> wrote:

I think we should still lead with a truncated version of the table. It is very powerful that even IPCC sees no trend in most impact drivers. So omit the "emerging by 2050" and "emerging by 2100" columns. That way it's only about detection.

SEK

PS Of course, need to note this truncation in the Table caption.

From: Judith Curry <curry.judith@gmail.com>

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Subject: Re: Ch 8 Extreme weather - new thread

several comments

I don't like table 12.12 in this chapter, since the chapter is about detection -- not attribution and not projections (and I detest showing extreme emissions scenario)

The general idea of this re-organization is good

I would lead with temperature extremes and then precip extremes, since the IPCC has actually detected a change in these

I will redo the hurricane one (ryan maue's figure is good but i have other suggestions)

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Taking Judy's reduced collection of excerpts I put each one at the start of its section so that any contextual discussion occurs right away. To make these easier to find I pasted them from Judy's document in gray text. I added in the NCA17 heat wave chart. I also put the IPCC Table 12.12 in with an explanation that it's not strictly speaking trend detection and we did attribution in Ch 7 but it's still helpful context.

The chapter sequence is:

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8.2 IPCC Table 12.12

8.3 hurricanes and TCs

8.4 Temperature extremes

8.5 Extreme precip

8.6 Tornadoes

8.7 Flooding

8.8 Droughts

8.9 Wildfires

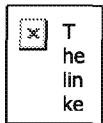
8.10 Summary

I took out the AI-generated summary that was in previously since it seemed overly focused on Table 12.12.

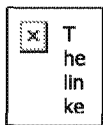
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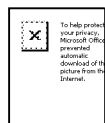
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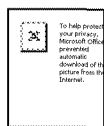
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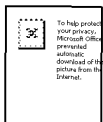
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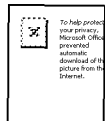
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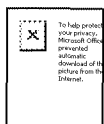
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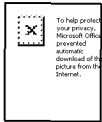
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Subject: Re: Ch 8 Extreme weather
Attachments: 8 Extreme weather.RM.May06.docx

Here's another edition of Ch 8 on extremes taking Judy's and John's points into account. The IPCC/NCA review is ported to an Appendix. I added a paragraph about LTP to the intro. I've incorporated the NE data. The bulk of the chapter is John's US temperature and precip data analysis with some additional material on wildfires, drought and TCs. For the US temperature extremes I moved the range figure to come just after the hot/cold extremes count because I think they both make a coherent point namely that the US becoming less extreme because heat events are rising more slowly than cold events are warming. There will still need to be an overall chapter summary but I'm going to move on to other chapters now. I'll put this in the Dropbox.

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I like John's material too which is why I included it and am working on the extended regional analyses. But on this topic people are heavily primed to believe that extreme weather of all kinds is getting worse due to climate change. The assertion shows up everywhere climate change is discussed including in academic papers. I think it is very valuable to show people that neither the IPCC nor the NCA support such this view. We should at least lead off with the summary table. The library of quotes can go to an appendix but I have found in my public speaking that they have considerable persuasive force for most people. We also need to address floods, droughts, hurricane landfalls, tornadoes etc. I don't see any reason to delete all that material.

On Tue, May 6, 2025 at 9:22 AM Judith Curry <curry.judith@gmail.com> wrote:

I actually liked John's chapter. I would have retitled it "US temperature and rainfall extremes"

I think this is more relevant than a complete rehash of everything the last 3 IPCC reports have stated for every conceivable severe weather event.

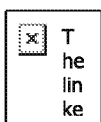
John's version meshes very well with my version of chapter 6. Read especially section 6.4 of my chapter. I note a discrepancy between chapters 11 and 12 in terms of detecting and attributing extreme events. This is the main point in my opinion, there is ambiguity in all this. Lets focus on pointing out the problems/challenges, and topics that are particularly relevant for the US

On Mon, May 5, 2025 at 7:47 PM Ross McKittrick <ross.mckitrick@gmail.com> wrote:

I have wrangled the extreme weather chapter into something I hope flows better and is more readable. I adopted Judy's editorial changes and then the new changes I made are in red. I added some new Figures showing results on PC and SE data and will add the NE chart when I get the data. I also made some labeling suggestions including for the 3 rainfall charts that are hard to understand. Section summaries and an overall summary are still needed.

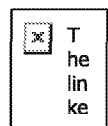
Ross

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8 Extreme weather in the US and elsewhere

8.1 Introduction

Weather extremes, usually related to temperature and/or precipitation, often disrupt infrastructure and therefore human health and thriveability. Indeed, the ability of any surface-dwelling species to live productively is somewhat constrained by these extremes which in essence create the bounding limits for survival. The issue here is whether these extremes, and their attendant potential danger, may be changing and if so whether the change is in response to increases in infrared-absorbing greenhouse gases (GHGs) (e.g., IPCC AR6 Seneviratne et al. 2021).

Unfortunately, the sample of time from which we are able to quantitatively analyze variations in extreme events is quite brief, around 130 years. This period certainly does not begin to contain all of the extreme events that the climate system is able to create naturally. Over geologic time the climate system has generated an (essentially) infinite variety of patterns and extremes which humans have never observed, and thus do not enter our databases from which extreme statistics are determined [see xx and xx below]. Thus, assuming that a new climate pattern or event hitherto not experienced in our lifetime is somehow must therefore be the result of enhanced GHG concentrations requires the assumption that natural variations are insignificant.

This is especially true for precipitation events. The hydrological literature has long noted the phenomenon of *Long Term Persistence* (LTP) in rainfall data (Hurst 1951, Cohn and Lins 2005, Markonis and Koutsoyiannis 2015). LTP has a formal mathematical definition but it can be thought of intuitively as the presence of natural variations with strong autocorrelation properties that result in cycle-like behavior on long time scales. The presence of LTP requires very long data samples to obtain accurate estimates of variance; analysis of data samples that are short relative to the LTP scale will tend to yield underestimated variances which in turn yields overstated significance of apparent trends and underestimation of the likelihood of extreme events (Cohn and Lins 2005).

With this caveat in mind we examine the evidence for changes in weather and climate extremes. It has become routine in media discussions, government and private sector discussions and even in some academic literature to make generalized assertions that extreme weather of all types is getting worse due to GHGs and climate change. Yet expert assessments have not typically drawn such sweeping conclusions and instead have emphasized the difficulty both of identifying specific trends and establishing a causal connection with anthropogenic forcing. In the Appendix to this chapter we provide excerpts of these finding from previous IPCC and NCA assessments.

8.2 Global and continental indicators of extreme weather trends

8.2.1 Tropical Cyclones (TCs)

Hurricane strength records for the North Atlantic and the Western Pacific go back to 1950 and the record does not show an increase in either total or major TCs. Figure 8.1 was published by Roger Pielke Jr. as an update to the Best Track data series originally presented in Weinkle et al. (2012).

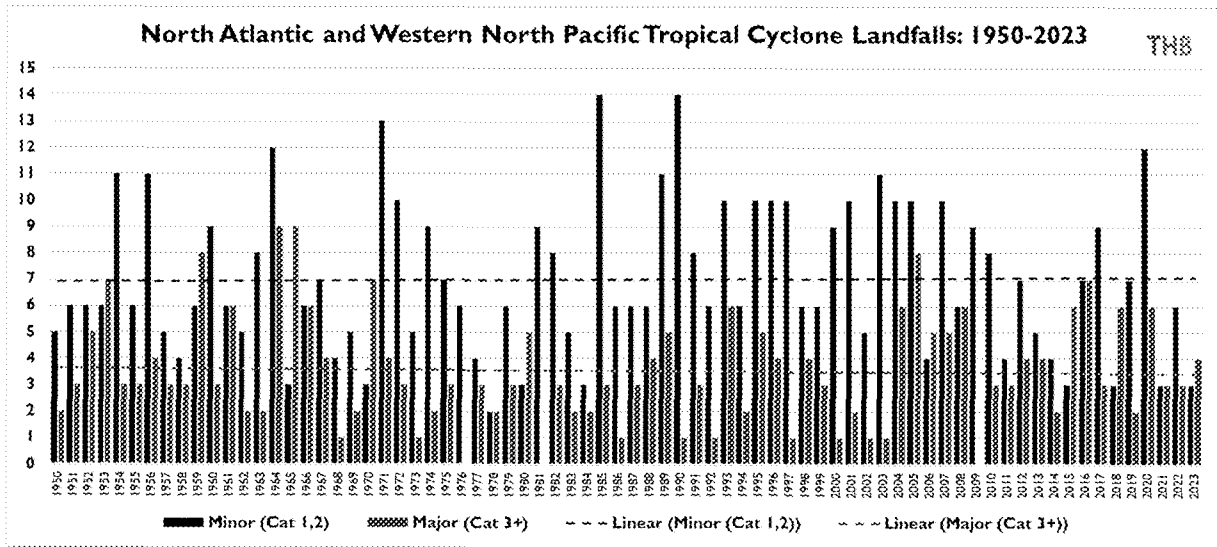


Figure 8.1. Tropical Cyclone Landfalls. Source: <https://rogerpielkejr.substack.com/p/global-tropical-cyclones>, Weinkle et al. (2012)

After 1980, as shown in Figure 8.2, which reproduces data from the Climate Atlas of Dr. Ryan Maue neither the total number of hurricanes nor the frequency of major ones have become more common since 1980, indeed both have trended down since the 1990s:

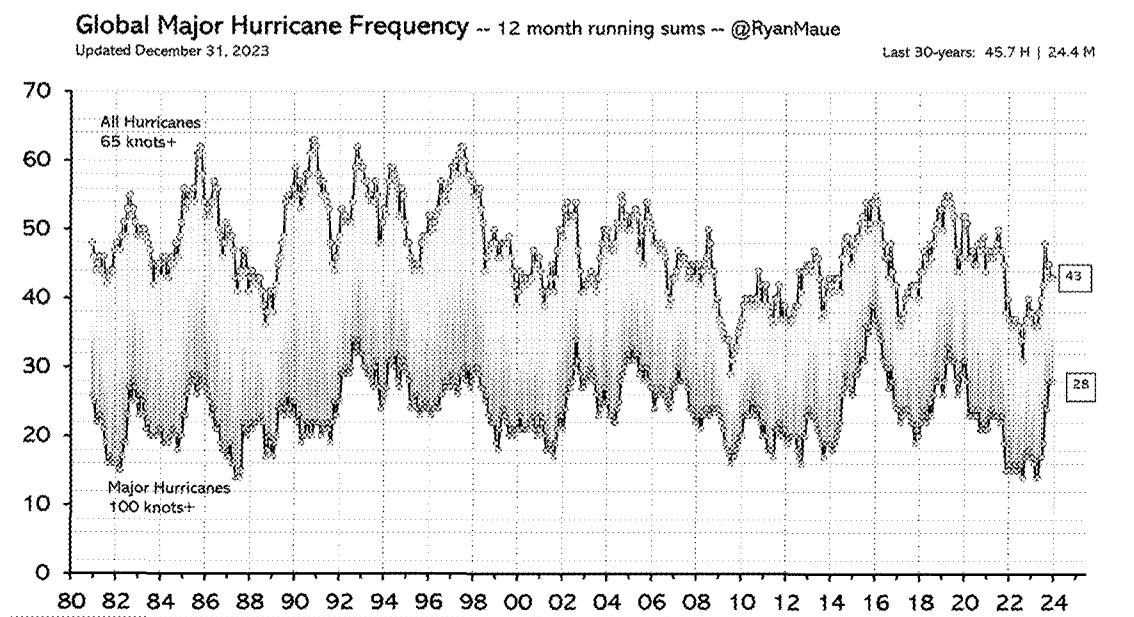


Figure 8.2: Global hurricane frequency. Source: Maue (2024)

A metric that combines the number and frequency of TCs is the Accumulated Cyclone Energy or ACE Index maintained at Colorado State University, shown in Figure 8.3.

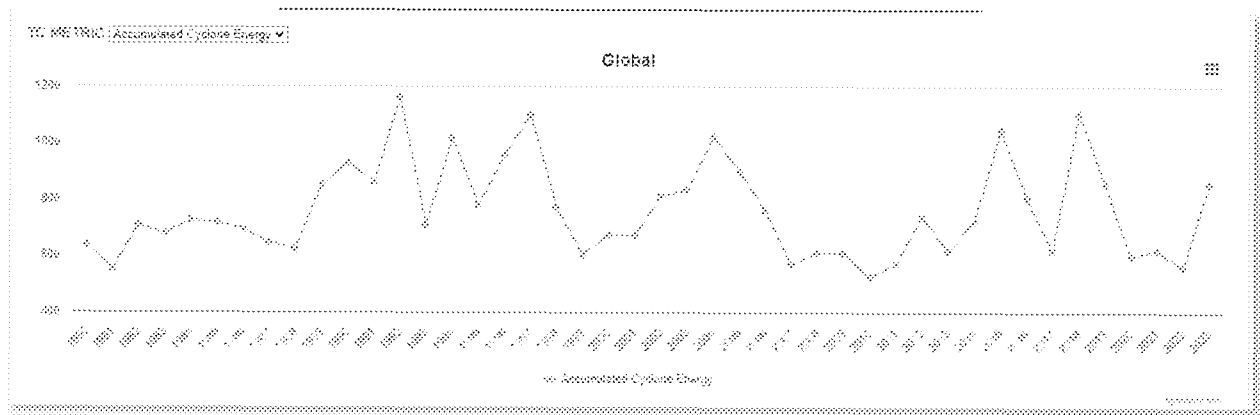


Figure 8.3: Global Accumulated Cyclone Energy. Source: Klotzbach (2025)
<https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=global>

As is clear, it is also not increasing and since 1990 has declined slightly.

Climate models project declining hurricane formation rates in a warming climate (Chand et al. 2022). Climate models also project fewer Tropical Cyclones under future global warming, and even though models project they will increase in strength, the annual averages of rainfall maxima decline (Stansfield et al. 2020). Note that Tu et al. (2024) report that the Power Dissipation Index (PDI), a measure of the destructiveness of hurricanes, has either remained unchanged or has declined in all global oceanic basins since the mid-1990s.

8.2.2 Wildfires

As shown in Figures 8.4 and 8.5 global wildfire activity as measured by European Space Agency peaked over a decade ago and shows a downward trend since.

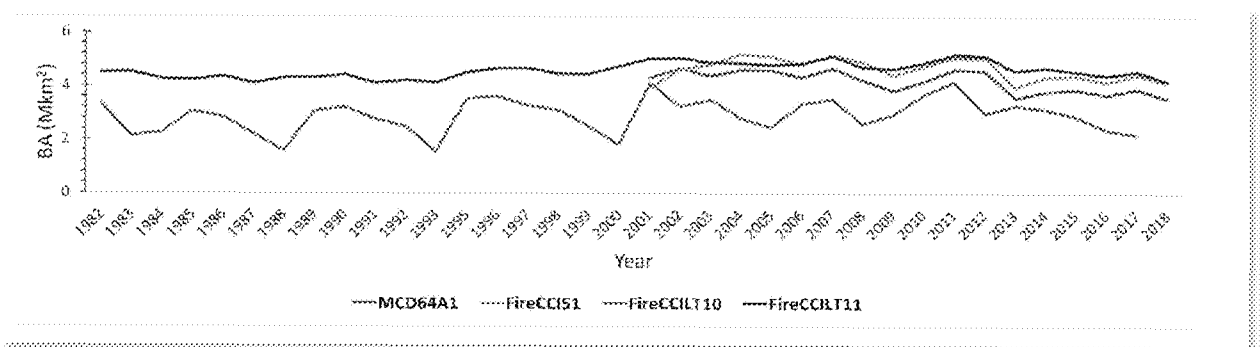


Figure 8.4: Global wildfire 1982-2018. Source: Copied from Oton et al. (2021). Note: the different coloured lines represent different data products based on satellites and algorithms used.

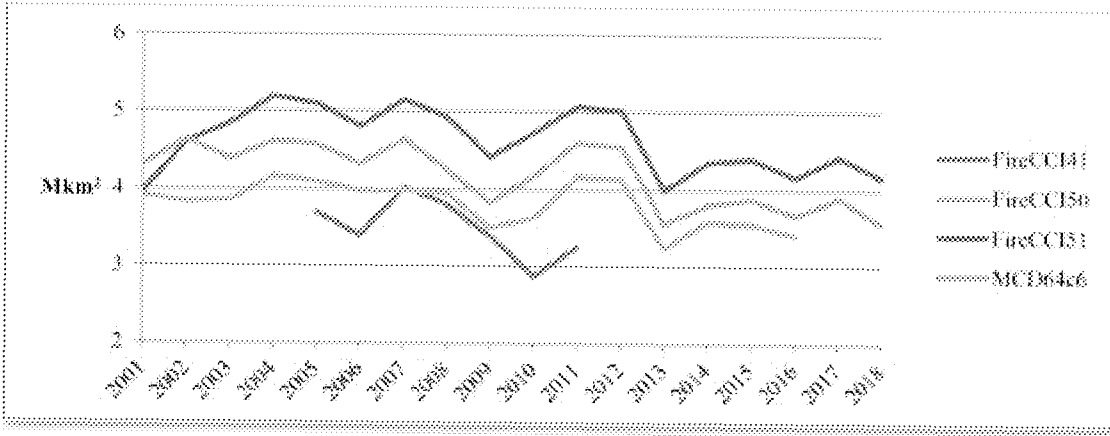


Figure 8.5: Global wildfire 2001-2018. Source: Copied from Lizundia-Loiola et al. (2021). Note: the different coloured lines represent different data products based on satellites and algorithms used

US data from the National Interagency Fire Centre (NIFC) from 1926 to 2023 are shown in Figure 8.6.

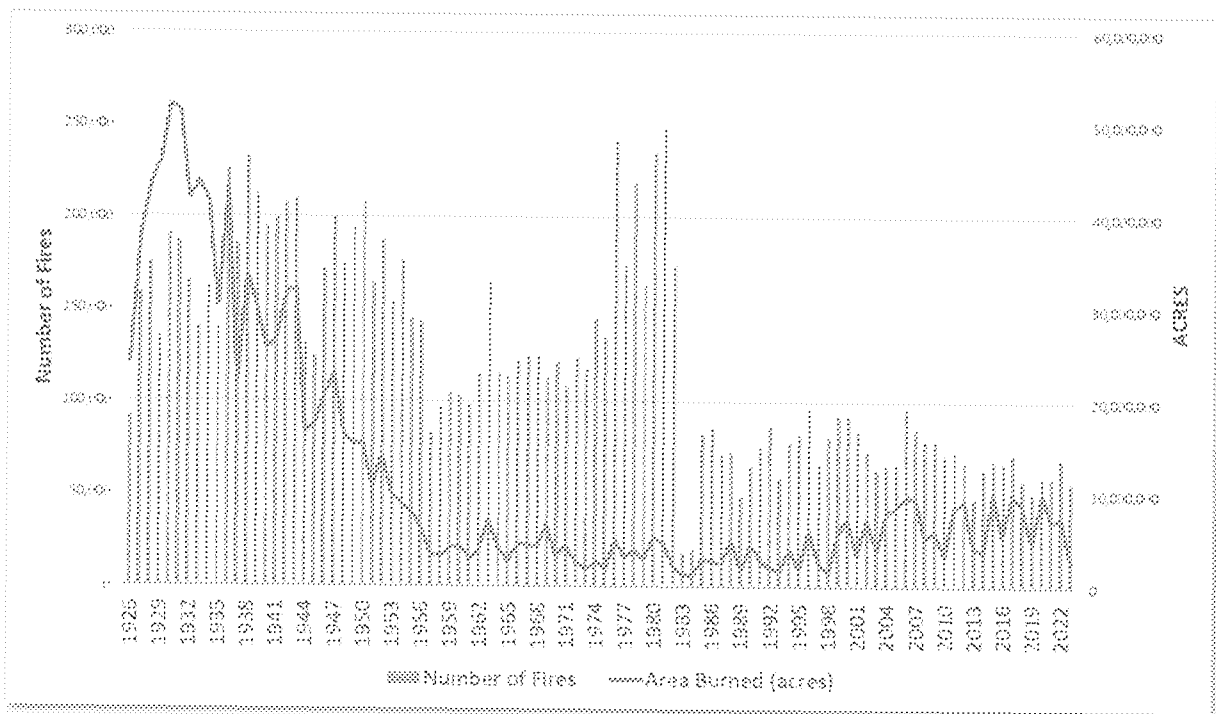


Figure 8.6: US wildfires 1926 to 2023. Source: National InterAgency Fire Centre data Pre-2017 (archived) https://web.archive.org/web/20200212033452/https://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html. 2018-2023: <https://www.nifc.gov/fire-information/statistics/wildfires>

Note the NIFC has removed the pre-1960 data from its current website. They claim it is because measurement methods changed after 1960. This explanation seems inadequate since agencies blend temperature and extreme weather data series in other context when measurement systems changed. In this case if anything the measurement of wildfires has improved since the early 20th

century so any bias will be towards understating early wildfire counts. Nonetheless just focusing on the post-1985 interval the number of fires is not increasing. The area burned did increase but only until about 2007.

It is difficult to establish a natural baseline for wildfire activity because of active fire suppression activity since 1900. Paleoclimatic evidence indicates, however, that past wildfire activity was much higher than at present. Marlon et al. (2012) used sedimentary charcoal layers to reconstruct fire history of western US for the past 1400 years. They also fit a model to predict expected fire activity as a function of climatic conditions. The results are summarized in Figure 8.7 below (from Figure 2 in their paper).

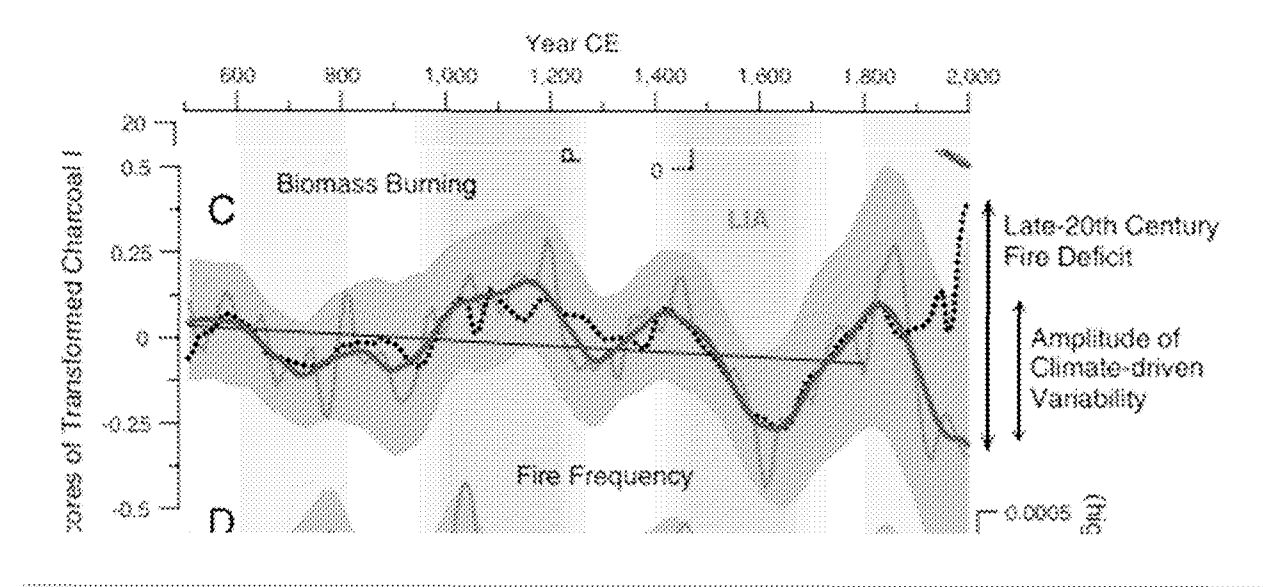


Figure 8.7: Fire frequency and fire deficit in the US. Source: Copied from Marlon et al. (2012)

In their figure the red line shows the smoothed charcoal record and the black dotted line shows the predicted charcoal record based on the statistical model. The gap at the end implies there has been a growing wildfire deficit over the 20th century. In other words, however much fire was observed in the 20th century it was less than what would have been observed in previous centuries based on the climatic conditions. Parks et al. (2025) likewise find that despite the recent increase in wildfire burn area in North America, relative to historical wildfire regimes there remains a significant wildfire deficit.

8.2.3 Precipitation

Figure 8.8 shows that US long term data from NOAA shows an insignificantly increasing tendency toward extreme wetness (+0.001% per year)

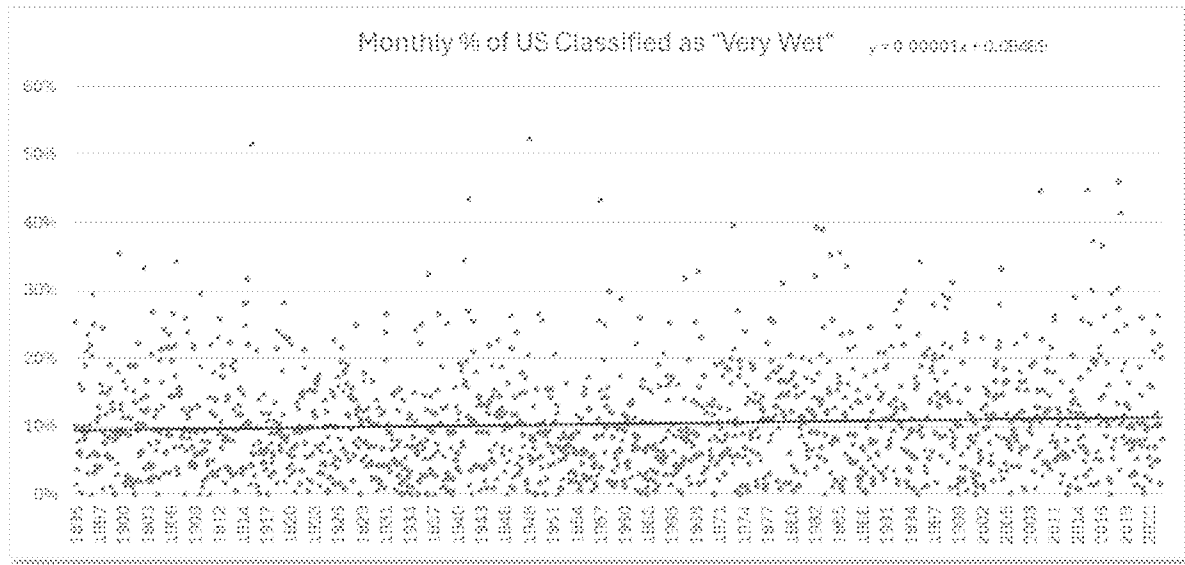


Figure 8.8: Long term US wetness (%). Source: NOAA
<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>

Precipitation will be discussed further in the review of CONUS data below.

8.2.4 Drought

As shown in Figure 8.9 US long term data (NOAA) shows an insignificantly declining tendency toward extreme dryness (-0.001% per year)

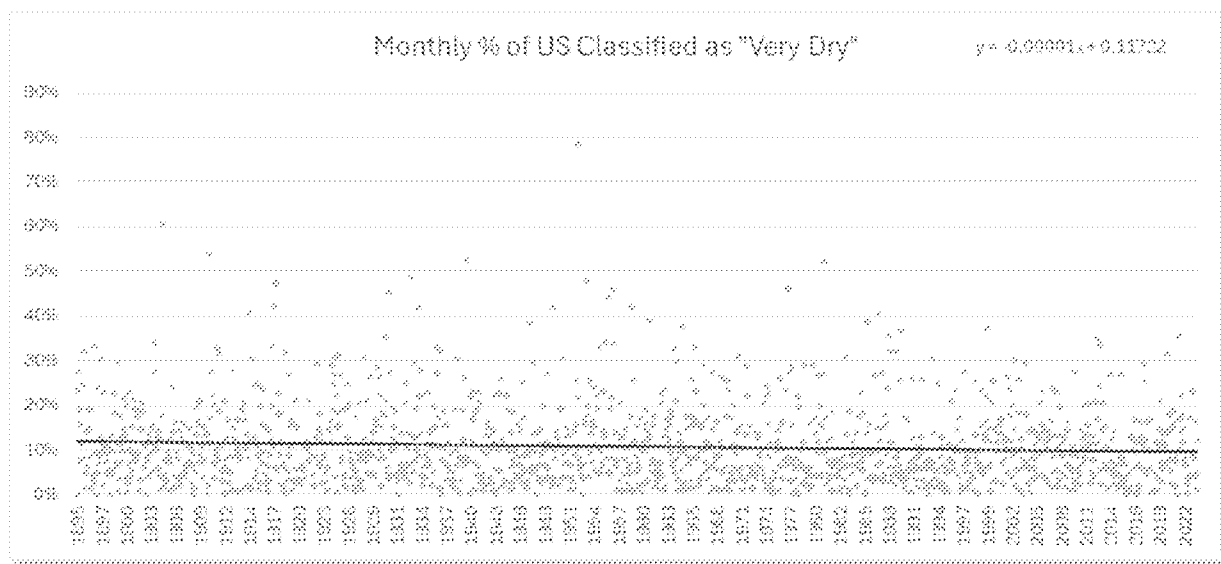


Figure 8.9: US dryness (%) 1895—2023. Source: NOAA
<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>

Kogan et al. (2020) examines a 38 year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change: “it is possible to state firmly that global and main grain countries’ drought area and intensity trends have not been following global climate warming since 1980’s.”

8.3 Analysis of Conterminous US (CONUS) data on temperature and precipitation extremes

8.3.1 CONUS daily temperatures are becoming less extreme

Daily maximum temperatures in the warm season (TMax, May-Sep) and daily minimum temperatures in the cold season (TMin, Dec-Mar) are available beginning in Dec 1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (Quinlan et al. 1987, Karl et al. 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although errors certainly reside in the dataset, with over 1,000 stations any underlying signal we discover-can be characterized by relatively high confidence.

We begin with the question of whether the occurrence of daily record high or low temperatures changed has changed since Dec 1898. Each warm-season has 153 days (1 May to 30 Sep) and each cold-season has 122 days (1 Dec to 31 Mar). For each of these days and each of the stations station we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time, ~~on average, that a station would experience an average each year of 1.21~~ the expected number of records for TMax would be 1.21 per year and ~~0.96 records for TMin 0.96~~ per year. Figure 8.10 indicates the observed distribution in time of the occurrence of these extreme events.

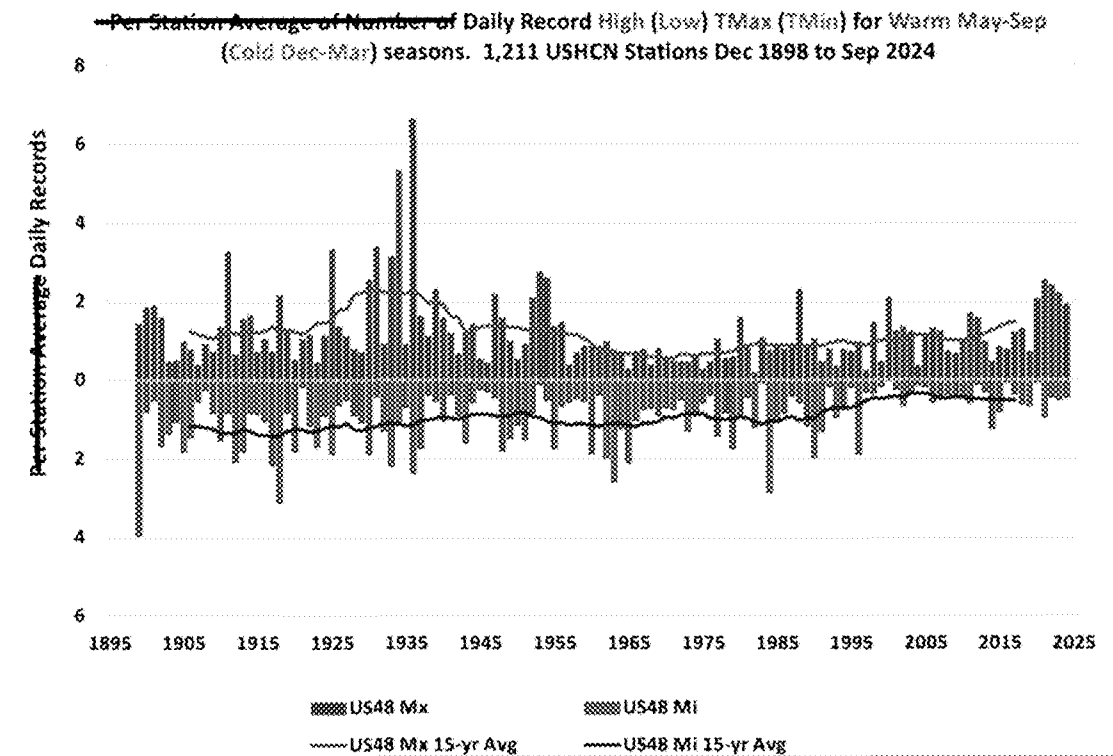


Figure 8.10. I don't think these are per station. I think they are totals across all 1,211 stations every year. E.g. there couldn't be 4 cold records per station in 1899. Per-station-average of Number of daily record High (red) and Low (blue) for warm and cold seasons in the CONUS. The lines represent 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92% of observations in the 126-year period since Dec 1898.

The results indicate a common feature in many metrics of warm-season extremes in the CONUS - the exceptional heat of the 1920s and especially the 1930s. On a per-station average, 60% of the TMax records and 59% of the TMin records occurred in the first half of the period (1899-1961). On the cold side other-extreme, the Valentine's Day Arctic outbreak in Feb 1899 stands as the most extensive cold extreme experienced by the CONUS, with 1917 2nd. Overall, the number of cold records has declined, especially over the past 25 years. The frequency of cold records has declined, especially over the past quarter of the period in which only 13% of the extreme cold events were measured. In contrast, 25% of the extreme TMax records were achieved in the last quarter in accordance with statistical expectations. These general features have been noted in past assessments (IPCC AR5, IPCC AR6, NCA4, NCA5). Combining the two records the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 8.11. For each station and for each year the hottest warm season and coldest cold-season temperatures were calculated and converted to anomalies relative to the station's long term warm and cold season (respectively) averages. Then the differences between these were computed by station and averaged over all stations, thus yielding an annual measure of the expected range of local extreme temperatures for each year. Figure 8.8 shows the 15-year trailing average of this measure which has clearly declined over the past century.

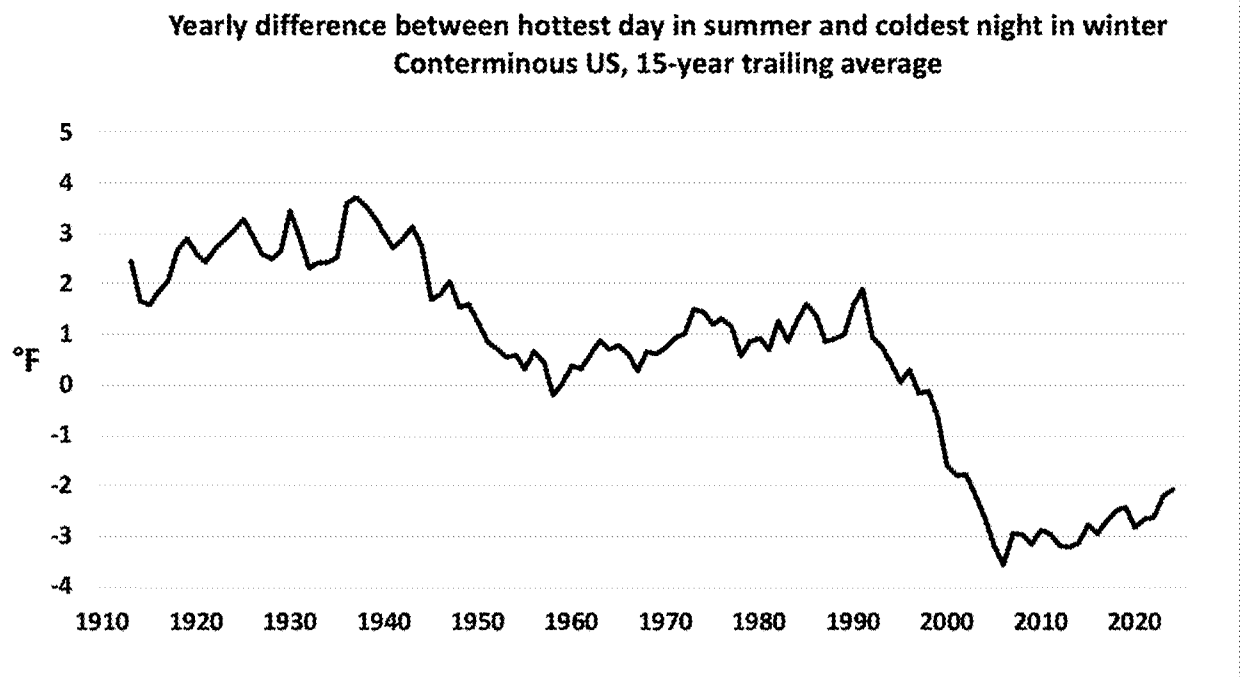


Figure 8.11. 15-year trailing average of the difference each year of each station’s hottest warm-season TMax and coldest cold-season TMin relative to the long-term average.

Figure X shows that the The average difference for each station between the hottest summer TMax and coldest winter TMin has declined about 5°F in the past 126 years. The decline is due mostly to warming winter TMin, but a decline in the magnitude of summer TMax is also a factor. The rise in TMin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (Spencer et al. 2025).

Summarizing Figures 8.10 and 8.11, while temperature extremes are regularly experienced in the US and attract a great deal of media attention, long term records show the US climate has become less extreme over time when measured in terms of the range between warm season maxima and cold season minima.

8.3.2 Exceedances of a heat threshold

Under the heading of “The Risk of Temperature Extremes is Changing”, the most recent US National Climate Assessment report (NCA5) notes the increase in a threshold metric of number of days at or above 95°F, stating,

“The western US has been particularly affected by extreme heat since the 1980s ..., experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US.”

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS threshold statistics can be misleading. A region with many stations which have near 95°F TMax average temperatures in the summer might see large swings in the metric when only small changes in average temperature occur. Elsewhere with stations that either rarely or virtually always achieve 95°F TMax temperatures, a small change will not impact the results much at all. In the past 126 years, the average CONUS station experienced 129 days exceeding 95°F per 6-yr period, but the regional values range from 249 in the Pacific Southwest to 9 in the Northeast. Thus, one needs to view such threshold analyses with caution.

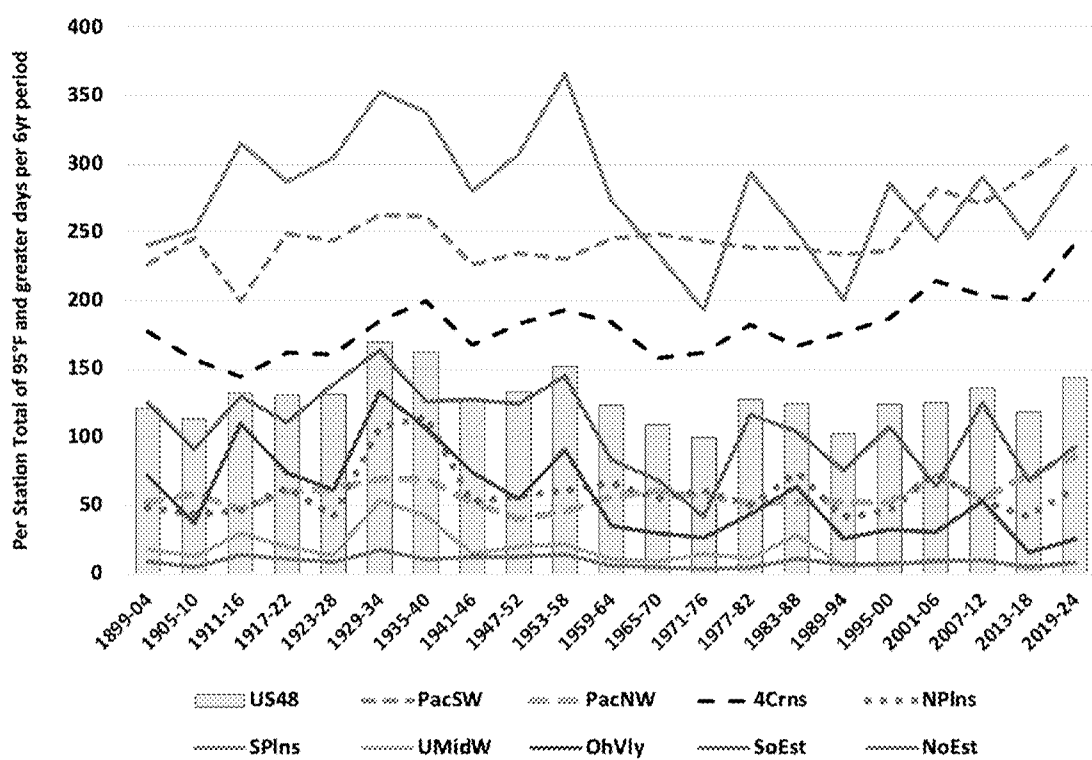


Figure 8.12. Per station average of Total number of days $\geq 95^{\circ}\text{F}$ in 6-yr periods, US 48 (bars) and regions (lines).

In Fig. 8.9 we see that only three of the nine regions, all in the West, have experienced upward trends for in the number of 95°F or hotter days. The entire CONUS as a whole has not and the other six regions have experienced declines. The NCA5 heading “The Risk of Temperature Extremes is Changing” suggests positive trends are now being observed, but that is not evidenced in the combined results of Fig. 8.9. That the “Risk” is changing can thus be applied only to forecasts which is addressed in section XX

8.3.3 Heatwaves

Of more impact than a single daily record is the phenomena of heatwaves, or consecutive days which exceed an extreme threshold. For this study, the metric will be the number of “Heatwave

Days” defined as the sum of all days in May-Sep each year which exceed the 90th percentile on consecutive days of at least seven days in length.

Why 7 days? Various HW definitions:

UK Met Office says 3 days above regional threshold in 25-28°C range

US National Weather Service says 2 hot days (no specified threshold)

WMO says at least five days at least 5°C above the local average.

So we need to ensure that the conclusions in this section are robust to heatwave definition

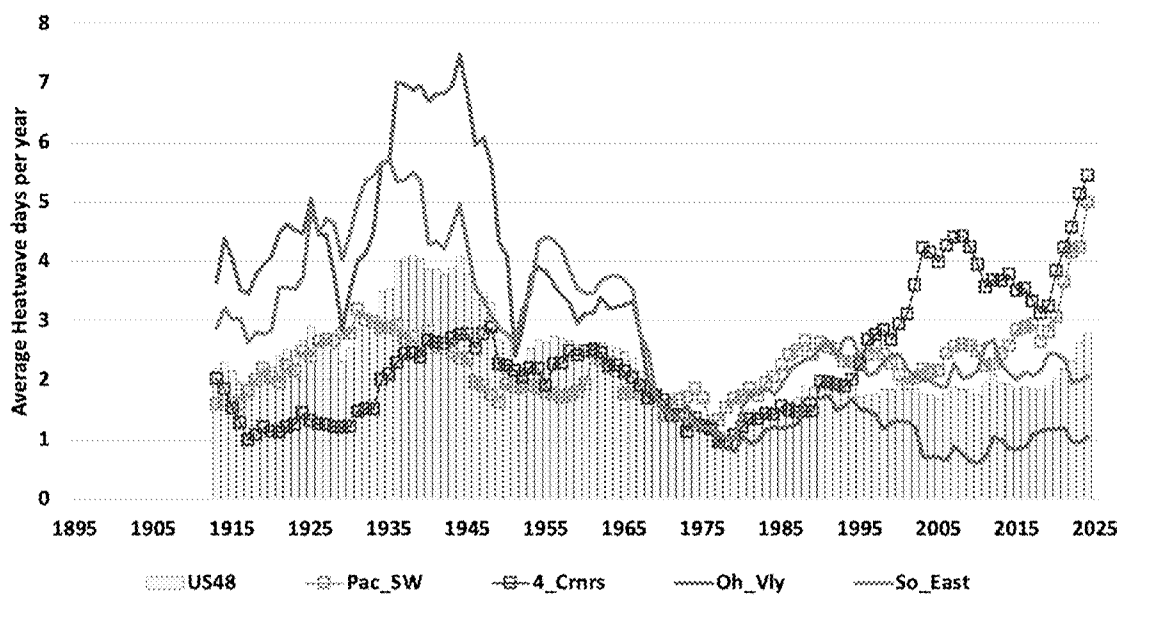


Figure 8.13 15-year trailing average of number of heatwave days per year per station in the CONUS (bars) and four regions: Pac_SW (orange squares, CA, NV), 4_Crnrs (red squares, AZ,NM,UT,CO), Oh_Vly (blue, MO, IL, KY, TN, IN, OH, WV) and So_East (green, MS, AL, GA, FL, SC, NC, VA).

Figure 8.13 indicates again the excessive heat of the first half of the 20th century, primarily in the eastern two-thirds of the nation, as seen in the sub-regional values for the Ohio Valley and the Southeast as examples. The West has seen a recent increase of heatwave days and the two sub-regions with the highest number are shown, the Pacific Southwest and the Four-Corners (NCA5). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20th century, but in the 21st century the patterns have favored heatwaves in the West.

Urban influences

Regarding a different heatwave metric, The NCA5 directs readers to the website <https://www.globalchange.gov/indicators/heat-waves> (USGCRP 2023) to view the number of urban heatwaves by decade from the 1960s. The figure reveals a monotonic increase in each decade from 2 per decade in the 1960s to 6 by the 2020s. The definition of a heatwave is ~~unusual~~ here—a period of at least 2 consecutive days when the apparent minimum temperature (combination of temperature and humidity) exceeds the 85th percentile. More importantly, the dataset is limited to the 50 largest cities in the US.

These results presented in USGCRP (2023) are entirely reasonable, but for reasons unrelated to GHG emissions. Urbanization in these cities is a major factor in the rise of TMin relative to TMax and to TMin at rural stations. Also, the decades of the 1960s and 1970s were the two coldest decades since the 1910's, so the starting date preconditions the time series to show warming. This does not dismiss the real rise in nighttime temperatures in major US cities and the impacts associated with these changes. However, we note for a variety of reasons that summer TMax (especially in rural areas) serves as better response variable for detecting potential changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs – ~~our concern in this document~~ (Christy et al. 2009). For the CONUS as a whole, the evidence in this section suggests GHG emissions have had little-to-no effect on heatwaves in the CONUS.

8.3.4 Extremes in daily precipitation.

Due to its stochastic and episodic character, precipitation requires careful statistical treatment to understand variability over long time periods. The US National Climate Assessments (NCA4, NCA5) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of the CONUS, especially the Northeast, when starting in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in extreme events are in the Northeast and least in the West, which is counter to the changes in temperature extremes shown above.

McKittrick and Christy (2019) examined long-term and consistent station observations of daily precipitation to test some of these NCA claims for the Southeast and West Coast. In neither case when the time series were extended back in time (as far as 1872 in some cases) or when starting later (1978) were the trends significant. For this report we update these findings with similarly constructed observations from 29 stations on the Pacific Coast (1893ff from San Diego CA to Blaine WA, see Figure 8.14), 24 stations in the humid Southeast (1872ff from Austin TX to Washington DC, see Figure 8.15), and 21 stations in the Northeast (1888ff from Buffalo NY to Portland ME—the region where trends are greatest, see Figure 8.16).

In the Pacific region over the whole sample the trend in average precipitation is negative and significant in Astoria and insignificant elsewhere. The trend in rainfall variance is positive and significant in Big Sur and insignificant elsewhere. The trend in daily maximum precipitation is positive and significant in Aberdeen and Big Sur and negative and significant in Newport and insignificant elsewhere. Averaged over all stations in the region none of these three trend parameters is statistically significant.

In the Southeast region over the whole sample the trend in average precipitation is positive and significant only in Mobile and Quitman, the trend in rainfall variance is positive and significant only in Mobile and the trend in daily maximum precipitation is positive and significant only in Vicksburg and Norfolk. Averaged over all stations in the region none of these three trend parameters is statistically significant.

The Northeast region exhibits a pattern of increasing average rainfall. The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall. The trend in rainfall variance is positive and significant only in Portland, Albany and Buffalo and insignificant elsewhere and not in the regional average. The trend in daily maximum precipitation is positive and significant only in Portland ME and Gardiner ME and insignificant elsewhere and not in the regional average.

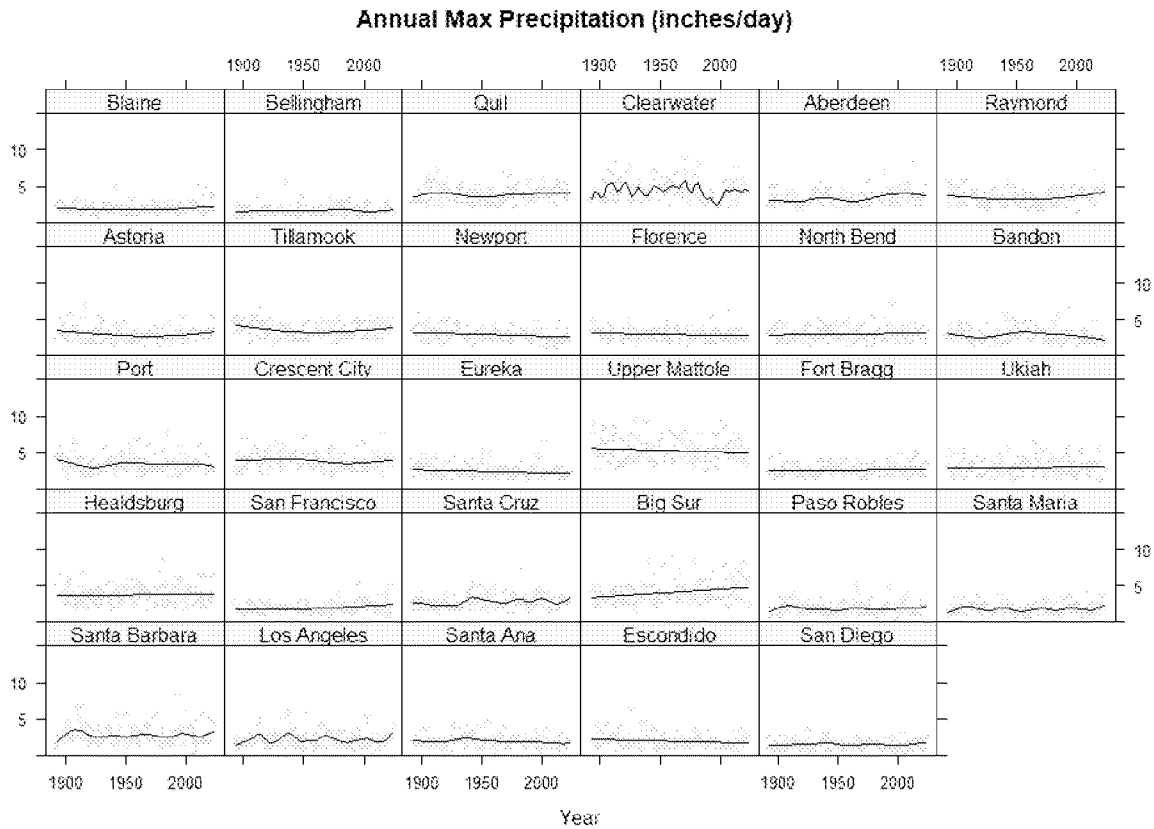


Figure 8.11 Annual maximum precipitation for 29 Pacific stations 1893 to present

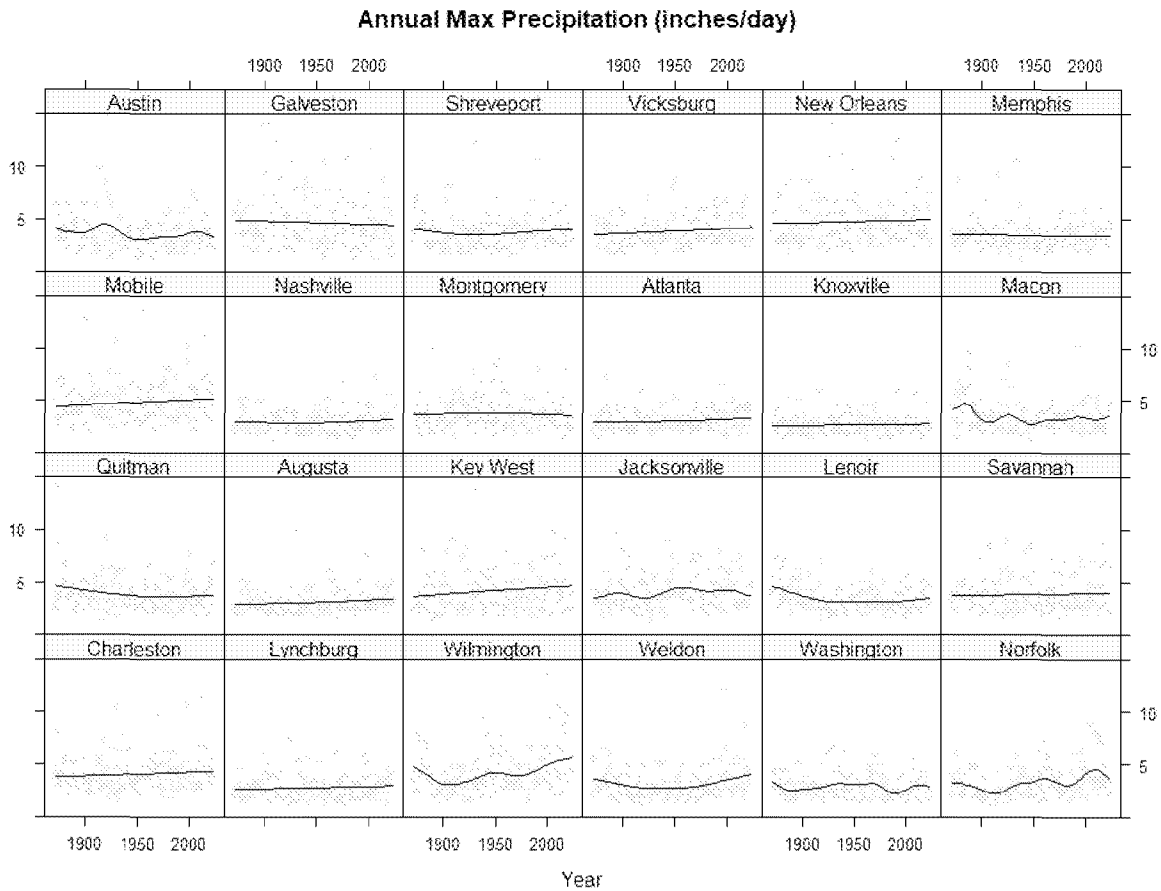


Figure 8.12 Annual maximum precipitation for 24 Southeast stations 1872 to present

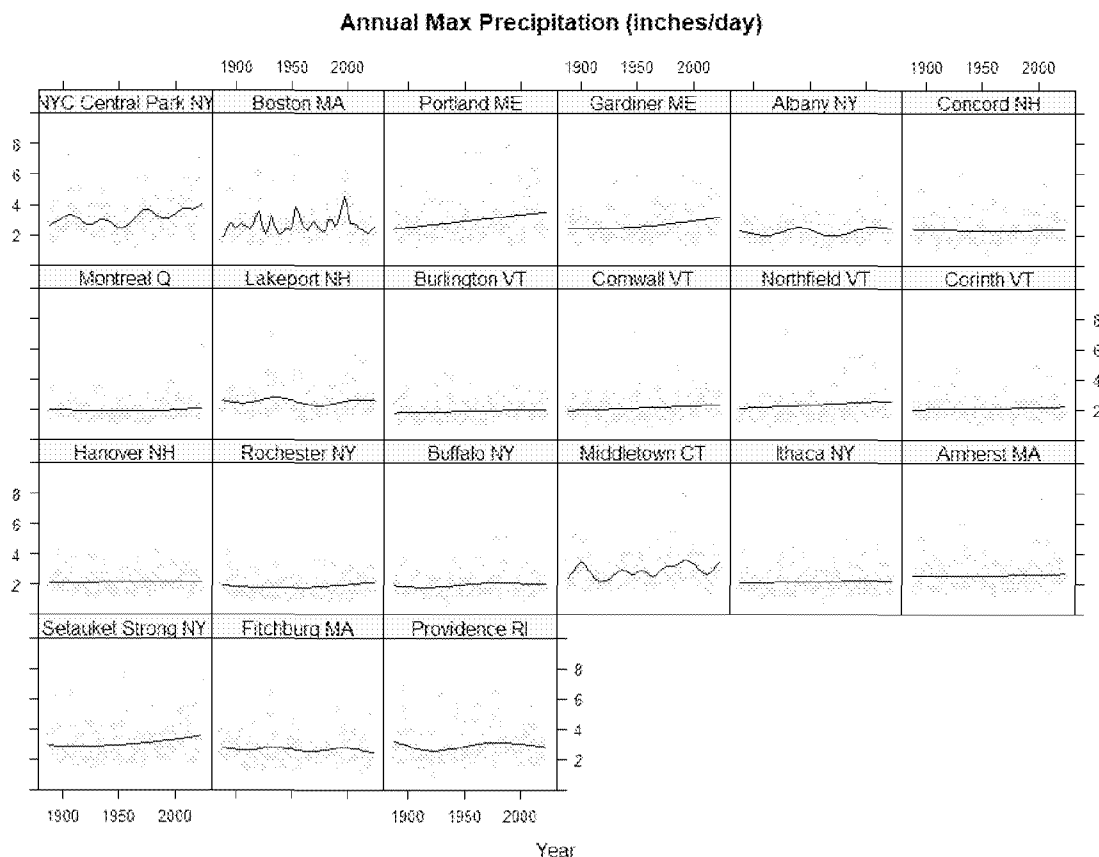


Figure 8.13 Annual maximum precipitation for 21 Northeast stations xxxx to present

Pacific Coast heavy rainfall events

The Pacific Coast receives considerable amounts of precipitation in from Atmospheric River (AR) events which often last more than a day or two. The worst-known such event in recent history was the ArkStorm that occurred between December 1861 and January 1862, which dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 15 feet of water (Brewer 1930, Porter et al. 2011). Six megastorms more severe than 1861–1862 have occurred in California during the last 1800 years, occurring at intervals of 200 years or so (Null and Hulbert 2007).

SIDEBAR: Perils of short data records

San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 8.1.

Event	Record (inches)	Year
3-day	6.94	2023
5-day	8.55	2023
14-day	12.62	2023

30-day	18.93	1998
--------	-------	------

Table 8.1: Extreme rainfall records, San Francisco, 1895-2024.

The records all cluster in the more recent data. 2023 appears to be an exceptional year and since it is near the end of the sample it would point to the possibility that the climate has shifted into a potentially more hazardous state.

But if we extend the record back to 1850 the picture changes. Table 8.2 shows that the record-setting events all happened in the 1860s. Furthermore 2023 is now not even in 2nd place but falls to 3rd or 4th. Also, comparing the records of the two charts the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1998 and 2023 events, with 14- and 30-day totals about 50 percent higher.

Event	Record (inches)	Year	Rank of 130-yr extreme
3-day	8.85	1867	3
5-day	9.80	1867	3
14-day	19.05	1862	4
30-day	28.25	1862	2

Table 8.2: Extreme rainfall records, San Francisco, 1850-2024.

However, the characterization of the range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter et al. (2011) discovered that in the past 1,800 years at least six megastorms that were more intense than the devastating 1861-62 ArkStorm struck the region. Thus, such extreme events have impacted the region about every 300 years, though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability. Accurate representation of the full range of natural variability is necessary for any attribution analyses (section 6.4). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time-sample of 130 years provides an underestimation of the extreme value by up to 50% determined when adding only 45 more years of observations. Compared to millennial-scale paleoclimate evidence, an even greater underestimation would occur.

We examine occurrences of 5-day deluges as follows. In a 130-year span there are 26 5-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values. Each of those can be thought of as 1-in-5yr events. If there are no trends in precipitation then the total number of these events across all stations should be evenly spread out on an annual basis. In Fig. 8.14 we show the distribution in time of these events ~~the 26 heaviest 5-day precipitation totals (nominal 1-in-5yr occurrence)~~. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of these types of precipitation metrics, there is no indication of a tendency to ~~change~~ become more frequent over time.

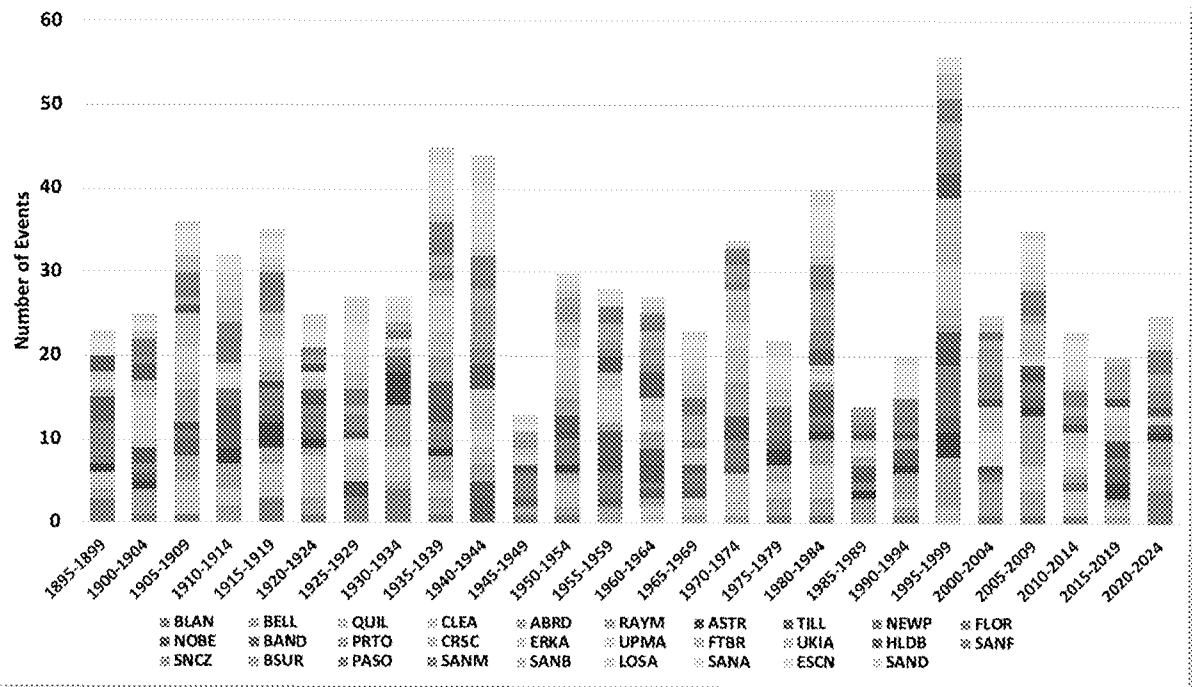


Figure 8.14. The time distribution by 5-year periods of the 26 heaviest occurrences for each station (i.e., nominal 1-in-5 year event). [JCurry: I FIND THIS DIAGRAM VERY DIFFIULT TO INTERPRET, EVEN THE STATION NAMES] [RM: I recommend removing the colour coding and simply showing the totals across all locations. Color-coding the locations does not add useful information and makes the chart confusing.]

Southeast heavy rainfall events

The temporal pattern of 5-day totals of the 1-in-5yr heavy events in the humid Southeast (Figure 8.15) is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA4 and NCA5 of a tendency for an increasing frequency of heavy events, due to a temporal clustering of tropical storms, from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events.

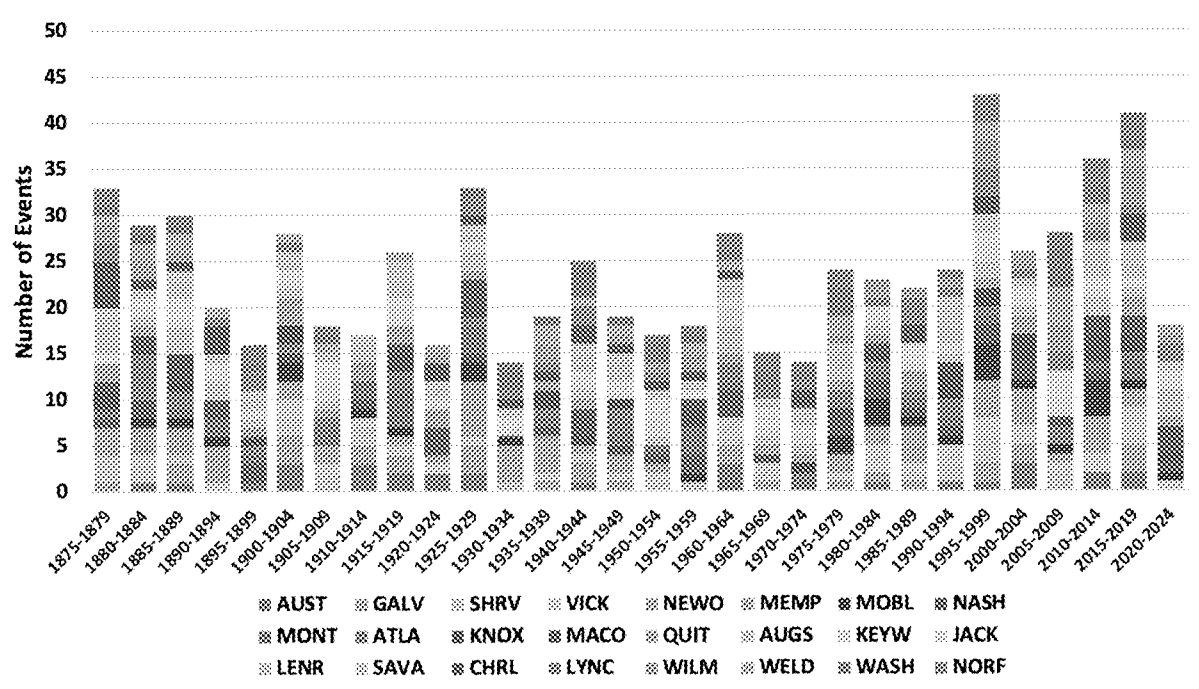


Figure 8.15. As above but for the 30 heaviest 1-in-5yr events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1875-2025. Figure X. The time distribution by 5-year periods of the 26 heaviest occurrences for each station (i.e., nominal 1-in-5 year event). [JCurry: I FIND THIS DIAGRAM VERY DIFFIULT TO INTERPRET, EVEN THE STATION NAMES] [RM: I recommend removing the colour coding and simply showing the totals across all locations. Color-coding the locations does not add useful information and makes the chart confusing.]

Northwest heavy rainfall events

Fig. 8.16 shows the 27 (1-in-5yr) heaviest 3-day events for the last 135 years in 21 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest variations in time. In this region, 72% of the events occur during June to October and are dominated by tropical incursions of hurricanes, tropical storms or tropical storms that transition to extratropical systems.

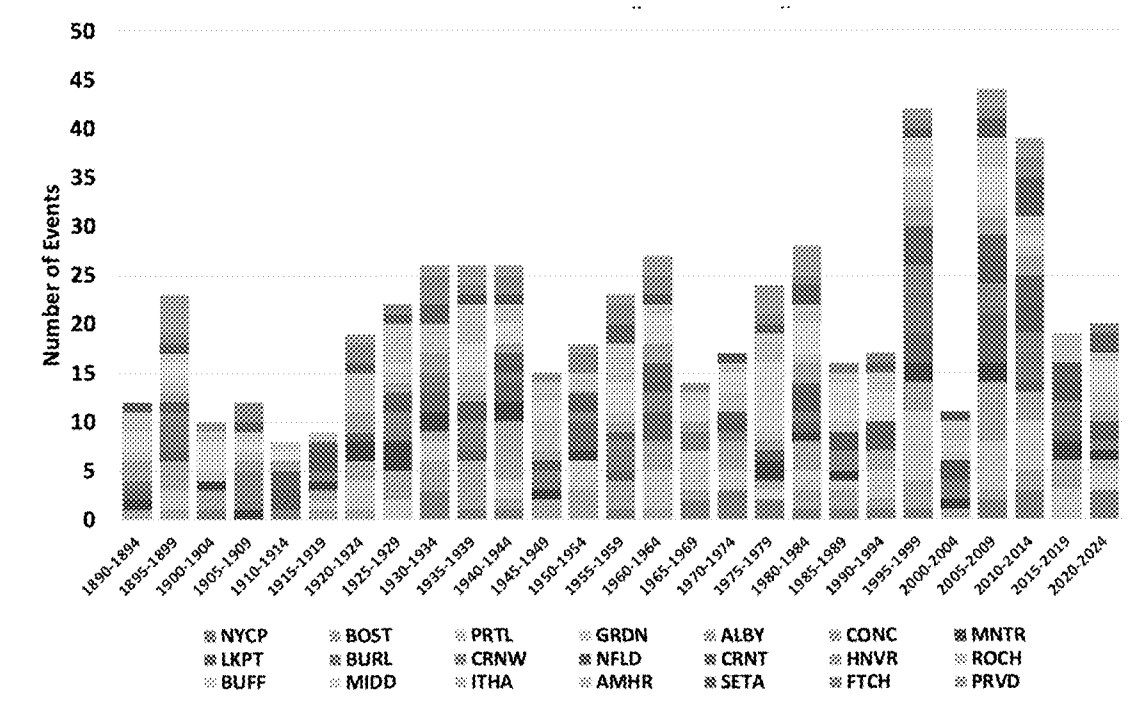


Figure 8.16. Time distribution of the heaviest 27 (1-in-5yr) heaviest 3-day precipitation events for 21 stations from NY to ME, including Montreal. AGAIN I FIND INTERPRETING THIS FIGURE VERY DIFFICULT [RM: I recommend removing the colour coding and simply showing the totals across all locations.]

Howarth et al. (2019) report differences in the Northeast between two 18-year periods: 1979-96 and 1997-2014 (a similar region as in Fig. 8.16 that includes PA and NJ) of various precipitation extremes, one of which indicated a dramatic increase (317%) in the 24-hr events involving at least 6 inches of rainfall. This high increase is due to the very small numbers of such events of which there were only 6 in the first period and 25 in the second. Most of the stations did not record such an event suggesting these erratic, episodic events over brief, 18-yr periods, need scrutiny by additional statistical methods.

Using the information in Fig. 8.16 over the same years as Howarth et al. we find a 51% increase in the frequency of heavy events between the two periods. One can see in Fig. 8.16 that it was unfortunate that Howarth et al. ended in 2014 prior to a return to the long-term average of such events.

A feature of Howarth et al. is the use of single day totals which is questionable because extreme events are often spread across the observation time boundary, so that stations measuring at 0700 LT versus those at Midnight will have differing results and which would then have major impacts on counting rare events. We use the 3-day totals in Fig. 8.16 to be sure to capture the extent of these short events. In any case, we can confirm that the period 1997 to 2014 provided a cluster of heavier events as Howarth et al. have documented.

Howarth's most remarkable claim (317% increase in 6" days) is potentially misleading because it is a threshold statistic (see above under Heat Threshold) and involving a ratio of small numbers over

a short period. The result is not representative of *relative* extreme events for the whole region since the majority of stations never experienced a 6" total. Fig. 8.16 above determines the same number of events for each station (27 heaviest events) whose heaviest events ranged from 4.4" to 12.5" and 27th heaviest event ranged from 3.3" to 5.0". This analysis thus normalizes the extremes so each station is equally represented. Note too that the period of record here is 135 years vs. 36 years in Howarth et al. Except for three 5-year periods between 1995 and 2014 there is nothing statistically remarkable about the results.

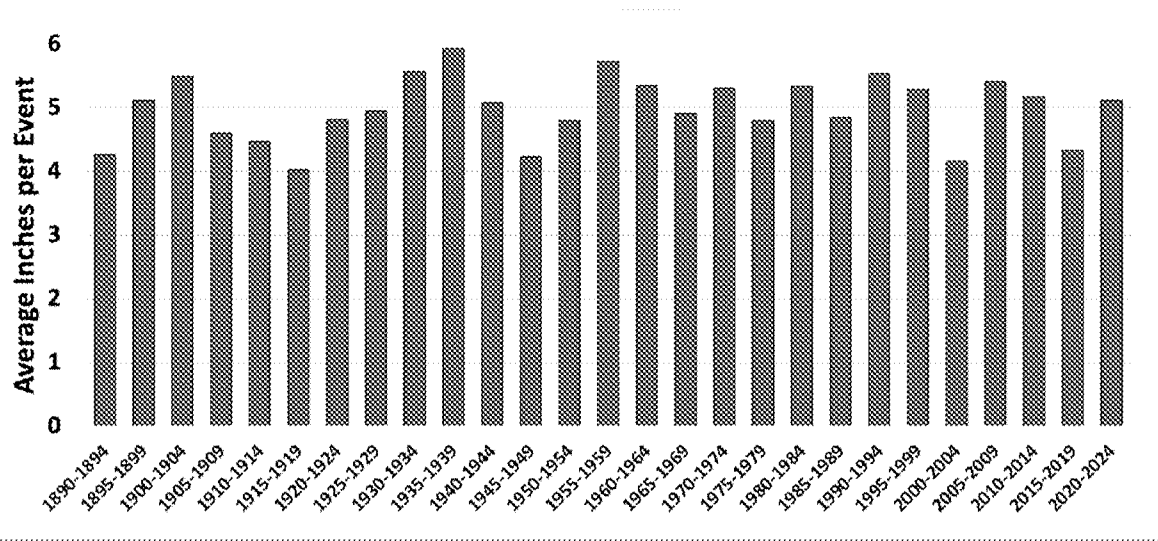


Figure 8.17. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

An interesting aspect of Northeast precipitation is that there has been no change in the amount of precipitation per heaviest event, as shown in Fig. 8.17. The trend is only +0.02"/decade. This result suggests that though there was an uptick in the number of events during the period 1995 to 2014 the events, individually, are not becoming more intense.

Jong et al. (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded, "The autumn extreme precipitation trend over the Northeast US is primarily attributed to tropical cyclone-related events since the 1990s." The question then becomes, was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs? Jong et al. examined CMIP-6 model output which suggests that there will be fewer such systems in the 21st century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 8.17 where the amount-per-event has remained steady over the 135-year period.

The evidence from the historical record of extreme precipitation events is generally not consistent from region to region so that inferences regarding trends and their projections are wrought with significant uncertainty. In most regions and perhaps all, it is our opinion that the very nature of the erratic and episodic character of extreme precipitation events renders the discovery of statistically significant changes a result yet to be achieved (McKittrick and Christy 2019).

URBAN HEAT ISLAND IS ALSO A FACTOR IN RAINFALL EXTREMES, MAYBE SOMETHING ABOUT THIS

ADD SUMMARY SECTION WITH MAIN CONCLUSIONS

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Appendix: Review of IPCC and NCA Findings on Extreme Weather

The sources we review will be denoted as follows:

SREX: The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (2012)

AR5: The IPCC *Fifth Assessment Report Working Group 1* (2013).

AR6: The IPCC *Sixth Assessment Report Working Group 1* (2021).

NCA17: The *US Climate Science Special Report of the Fourth National Climate Assessment* (2017) Volume I Chapter 6.

8A.1 Overview: IPCC Assessment of signal emergence in extreme weather types (AR6 WG1 Table 12.12)

Table 8A.1 reproduces the findings of AR6 Table 12.12 which indicates, for 34 major weather event and impact types, whether a signal of anthropogenic forcing has been detected in the historical record (column 1), whether such a signal is likely to emerge by 2050 under the extreme RCP8.5 scenario (column 2) and whether it is likely to emerge by 2100 under RCP8.5 forcing (column 3). As we discuss in Ch X on attribution there are conflicting messages within the AR6 regarding attribution of extreme weather. This Table is provided here for reference.

Several patterns stand out. First, out of the 34 weather impact categories an anthropogenic signal is asserted with *high confidence* in only four, and with *medium confidence* in a further four. For the rest the IPCC does not claim to have detected anthropogenic drivers. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean) hence are not measures of extreme weather. Also two of the four *medium confidence* assertions are related to ocean chemistry and thus are likewise not related to extreme weather. The IPCC does not assert a human influence on many non-temperature weather features such as wind, precipitation, flooding, drought etc.

Second, as shown in columns 2 and 3 the IPCC expects very few such signals to emerge this century *even under the most extreme forcing scenario*. As we discuss in Section 4.2 the RCP8.5 scenario is an implausible high-end storyline, it is not a “base case” or business-as-usual projection. Yet even still most weather impacts are not expected to exhibit an anthropogenic signal this century. As will be clear from the underlying report text, natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trends reversals over time.

Climate Impact Driver Type	Climate Impact Driver Category	Already Emerged in the Historical Record?	Emerging by 2050 in Most Extreme CO2 Emissions Scenario?	Emerging by 2100 in Most Extreme CO2 Emissions Scenario?
Heat & Cold	Average air temperature	YES in most regions	YES	YES
	More heat extremes	YES in most regions	YES in land regions	YES
	Fewer cold extremes	YES in a few regions	YES in many regions	YES
	Less frost	NO	NO	NO
Wet & Dry	Average Precip. (Increase or Decrease)	NO	YES (incr) YES (decr)	YES (incr) YES (decr)
	River flooding	NO	NO	NO
	Heavy precip & pluvial flood	NO	NO	YES in a few regions
	Landslide	NO	NO	NO

	Aridity	NO	NO	NO
	Hydrologic Drought	NO	NO	NO
	Agricultural & ecological drought	NO	NO	NO
	Fire weather	NO	NO	NO
Wind	Average wind speed	NO	NO	NO
	Severe wind storm	NO	NO	NO
	Tropical cyclone	NO	NO	NO
	Sand and dust storm	NO	NO	NO
Snow and Ice	Snow, glacier & ice sheet	NO	YES in a few regions	YES Arctic snow
	Permafrost	YES	YES	YES
	Lake & river ice	NO	YES	YES
	Arctic sea ice	YES	YES	YES
	Antarctic sea ice	NO	YES	YES
	Heavy snowfall and ice storm	NO	NO	NO
	Hail	NO	NO	NO
	Snow avalanche	NO	NO	NO
Coastal	Relative sea level	NO	YES	YES
	Coastal flood	NO	NO	NO
	Coastal erosion	NO	NO	NO
Open Ocean	Average ocean temperature	YES	YES	YES
	Marine heat wave	NO	NO	NO
	Ocean acidity	NO	YES	YES
	Ocean salinity	YES	YES	YES
	Dissolved oxygen	YES (Pacific & S. Ocean)	YES	YES
Other	Air pollution weather	NO	NO	NO
	Solar or IR radiation at surface	NO	NO	NO

Table 8A.1. IPCC AR6 summary of the probable emergence of an anthropogenic signal above natural climate variability for all global or regional “climate impact drivers” (CIDs) of concern for humans and ecosystems in response to increasing atmospheric greenhouse gas concentrations (primarily CO₂). Source: Table adapted from report of Working Group I, Table 12.12). Red = high confidence; yellow = medium confidence; green = no anthropogenic signal detectable above natural variability (50% confidence).

Taking wind as an example, the IPCC claims that an anthropogenic signal has not emerged in average wind speeds, severe windstorms, tropical cyclones or sand and dust storms, nor is one expected to emerge this century even under an extreme emissions scenario. The same applies to drought and fire weather. This table alone suffices to illustrate the gap between IPCC expert assessment of extreme weather and discussions of extreme weather in the popular press. As we show below the Table reflects longstanding conclusions of the IPCC and other assessment bodies. In the next few sections we will simply present without comment excerpts from past assessment reports.

Notes: in these excerpts bold-face emphasis is added. Italicized emphasis on *confidence* terms is in the original sources. Citations contained in quoted text can be found in the underlying reports but are not reproduced here.

8A.2 Flooding

SREX (p. 176)

In the United States and Canada during the 20th century and in the early 21st century, **there is no compelling evidence for climate-driven changes in the magnitude or frequency of floods.**

AR5 (p. 214)

AR4 WGI Chapter 3 (Trenberth et al., 2007) did not assess changes in floods but AR4 WGII concluded that **there was not a general global trend in the incidence of floods** (Kundzewicz et al., 2007). SREX went further to suggest that there was low agreement and thus *low confidence* at the global scale regarding changes in the magnitude or frequency of floods or even the sign of changes.

AR5 WGII assesses floods in regional detail accounting for the fact that trends in floods are strongly influenced by changes in river management (see also Section 2.5.2). Although the most evident flood trends appear to be in northern high latitudes, where observed warming trends have been largest, in some regions no evidence of a trend in extreme flooding has been found, for example, over Russia based on daily river discharge (Shiklomanov et al., 2007). Other studies for Europe (Hannaford and Marsh, 2008; Renard et al., 2008; Petrow and Merz, 2009; Stahl et al., 2010) and Asia (Jiang et al., 2008; Delgado et al., 2010) show evidence for upward, downward or no trend in the magnitude and frequency of floods, so that there is currently no clear and widespread evidence for observed changes in flooding except for the earlier spring flow in snow-dominated regions (Seneviratne et al., 2012).

In summary, **there continues to be a lack of evidence and thus *low confidence* regarding the sign of trend in the magnitude and/or frequency of floods on a global scale.**

AR6 (Ch 11 p. 1568)

The SREX (Seneviratne et al., 2012) assessed *low confidence* for observed changes in the magnitude or frequency of floods at the global scale. This assessment was confirmed by the AR5 report (Hartmann et al., 2013). The SR15 (Hoegh-Guldberg et al., 2018) found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. **While the number of studies on flood trends has increased since the AR5 report, and there were also new analyses after the release of SR15 (Berghuijs et al., 2017; Blöschl et al., 2019; Gudmundsson et al., 2019), hydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales.**

In summary, the seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). **Confidence about peak flow trends over past decades on the global scale is *low*, but there are regions experiencing increases**, including parts of Asia, southern South America, the northeast USA, northwestern Europe, and the Amazon, **and regions experiencing decreases**, including parts of the Mediterranean, Australia, Africa, and the southwestern USA.

US NCA17 pp. 240-41:

"The IPCC AR5 did not attribute changes in flooding to anthropogenic influence nor report detectable changes in flooding magnitude, duration, or frequency. Trends in extreme high values of streamflow are mixed across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude but does not provide robust evidence that these trends are attributable to human influences...

The complex mix of processes complicates the formal attribution of observed flooding trends to anthropogenic climate change and suggests that additional scientific rigor is needed in flood attribution studies. As noted above, precipitation increases have been found to strongly influence changes in flood statistics. However, in U.S. regions, **no formal attribution of precipitation changes to anthropogenic forcing has been made so far, so indirect attribution of flooding changes is not possible. Hence, no formal attribution of observed flooding changes to anthropogenic forcing has been claimed.**"

8A.3 Heatwaves

AR5 (p. 212 WG1)

Table 2.13 shows that there has been a *likely* increasing trend in the frequency of heatwaves since the middle of the 20th century in Europe and Australia and across much of Asia where there are sufficient data. However, confidence on a global scale is *medium* owing to lack of studies over Africa and South America but also in part owing to differences in trends depending on how heatwaves are defined (Perkins et al., 2012). Using monthly means as a proxy for heatwaves Coumou et al. (2013) and Hansen et al. (2012) indicate that record-breaking temperatures in recent decades substantially exceed what would be expected by chance but caution is required when making inferences between these studies and those that deal with multi-day events and/ or use more complex definitions for heatwave events. **There is also evidence in some regions that periods prior to the 1950s had more heatwaves (e.g., over the USA, the decade of the 1930s stands out and is also associated with extreme drought conditions** (Peterson et al., 2013) whereas conversely in other regions heatwave trends may have been underestimated owing to poor quality and/or consistency of data (e.g., Della-Marta et al. (2007a) over Western Europe; Kuglitsch et al. (2009, 2010) over the Mediterranean). Recent available studies also suggest that the number of cold spells has reduced significantly since the 1950s (Donat et al., 2013a, 2013c).

In summary, new analyses continue to support the AR4 and SREX conclusions that since about 1950 it is *very likely* that the numbers of cold days and nights have decreased and the numbers of warm days and nights have increased overall on the global scale, that is, for land areas with sufficient data. It is *likely* that such changes have also occurred across most of North America, Europe, Asia and Australia.

NCA17 (pp. 190-191)

Changes in warm extremes are more nuanced than changes in cold extremes. For instance, **the warmest daily temperature of the year increased in some parts of the West over the past century (Figure 6.3), but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease** (Table 6.2), most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]). The decreases in the eastern half of [the] Nation, particularly in the Great Plains, are mainly tied to the unprecedented summer heat of the 1930s Dust Bowl era, which was exacerbated by land-surface feedbacks driven by springtime precipitation deficits and land mismanagement. However, anthropogenic aerosol forcing may also have reduced summer temperatures in the Northeast and Southeast from the early 1950s to the mid-1970s, and agricultural intensification may have suppressed the hottest extremes in the Midwest.

Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). **Heat waves (6-day periods**

with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter (Figure 6.4). As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s.

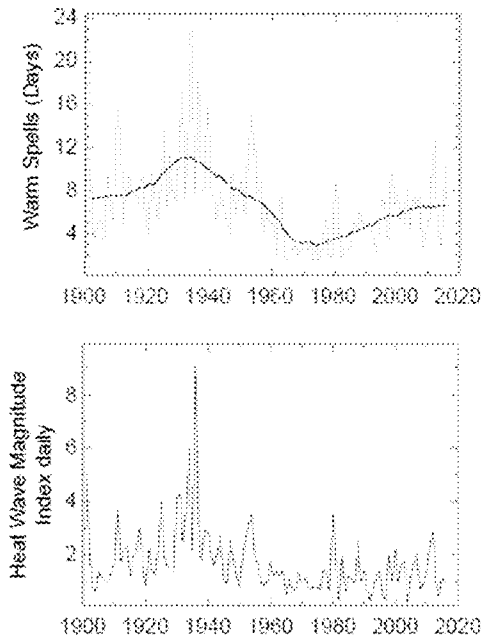


Figure 8.1: US Heat waves since 1900. Source: NCA17 Figure 6.4

AR6 (p. 1550)

In North America (Table 11.19), there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, **while there are more contrasting trends in the annual maximum daily temperatures** in parts of the USA (Figure 11.9; Lee et al., 2014; van Oldenborgh et al., 2019; Dunn et al., 2020).

8A.4 Extreme snowfall events

Note: extreme snowfall events in the US northeast are assessed in relation to winter Extratropical Cyclone (ETC) activity.

AR6 Ch 11. p. 1593

There is *high confidence* that snowfall associated with winter ETCs will decrease in the future, because increases in tropospheric temperatures lead to a lower proportion of precipitation falling as snow (O’Gorman, 2014; Rhoades et al., 2018; Zarzycki, 2018). However, there is *medium confidence* that extreme snowfall events associated with winter ETCs will change little in regions where snowfall will be supported in the future (O’Gorman, 2014; Zarzycki, 2018).

8A.5 Extreme precipitation

SREX (p. 142)

Recent studies have updated the assessment of the AR4, with more regional results now available (Table 3-2). Overall, this additional evidence confirms that **more locations and studies show an increase than a decrease in extreme precipitation, but that there are also wide regional and seasonal variations**, and trends in many regions are not statistically significant (Table 3-2)... Based on station data from Canada, the United States, and Mexico, Peterson et al. (2008a) reported that heavy precipitation has been increasing over 1950-2004, as well as the average amount of precipitation falling on days with precipitation.

AR5 (pp. 213-14)

In summary, further analyses continue to support the AR4 and SREX conclusions that **it is likely that since 1951 there have been statistically significant increases in the number of heavy precipitation events (e.g., above the 95th percentile) in more regions than there have been statistically significant decreases, but there are strong regional and subregional variations in the trends**. In particular, many regions present statistically non-significant or negative trends, and, where seasonal changes have been assessed, there are also variations between seasons (e.g., more consistent trends in winter than in summer in Europe). The overall most consistent trends towards heavier precipitation events are found in central North America (very likely increase) but assessment for Europe shows likely increases in more regions than decreases.

AR6 (p. 1560)

In North America, there is robust evidence that the magnitude and intensity of extreme precipitation has *very likely* increased since the 1950s. Both [one-day maxima] and [5-day maxima] have significantly increased in North America during 1950-2018 (Sun et al., 2020, also Figure 11.13). There is, however, regional diversity. In Canada, there is a lack of detectable trends in observed annual maximum daily (or shorter duration) precipitation (Shephard et al., 2014; Mekis et al., 2015; Vincent et al., 2018).

NCA17 pp. 213-14:

Detectability of trends (compared to internal variability) for a number of precipitation metrics over the continental United States has been examined; **however, trends identified for the U.S. regions have not been clearly attributed to anthropogenic forcing**. One study concluded that increasing precipitation trends in some north-central U.S. regions and the extreme annual anomalies there in 2013 were at least partly attributable to the combination of anthropogenic and natural forcing... **Based on current evidence, it is concluded that detectable but not attributable increases in mean precipitation have occurred over parts of the central United States**. Formal detection-attribution studies indicate a human contribution to extreme precipitation increases over the continental United States, but confidence is *low* based on those studies alone due to the short observational period, high natural variability, and model uncertainty.

In summary, based on available studies, it is concluded that for the continental United States there is *high confidence* in the detection of extreme precipitation increases, while there is *low confidence* in attributing the extreme precipitation changes purely to anthropogenic forcing.

8A.6 Tornadoes and severe convective storms

IPCC AR6 Sct. 11.7.3, p. 1594

Severe convective storms are convective systems that are associated with extreme phenomena such as tornadoes, hail, heavy precipitation (rain or snow), strong winds, and lightning.

The assessment of changes in severe convective storms in SREX (Chapter 3, Seneviratne et al., 2012) and AR5 (Chapter 12, Collins et al., 2013) is limited and focused mainly on tornadoes and hail storms. The SREX assessed that there is *low confidence* in observed trends in tornadoes and hail because of data inhomogeneities and inadequacies in monitoring systems. Subsequent literature assessed in the Climate Science Special Report (Kossin et al., 2017) led to the assessment of the observed tornado activity over the 2000s in the USA, with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days (*medium confidence*). However, there is *low confidence* in past trends for hail and severe thunderstorm winds. Climate models consistently project environmental changes that would support an increase in the frequency and intensity of severe thunderstorms that combine tornadoes, hail, and winds (*high confidence*), but there is *low confidence* in the details of the projected increase.

... In summary, because the definition of severe convective storms varies depending on the literature and the region, it is not straightforward to make a synthesizing view of observed trends in severe convective storms in different regions. In particular, observational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant, but their variability of occurrence has increased since the 1970s, particularly over the 2000s, with a decrease in the number of days per year, and an increase in the number of tornadoes on these days (*high confidence*). Detected tornadoes have also increased in Europe, but the trend depends on the density of observations.

... It is extremely difficult to detect differences in time and space of severe convective storms (Kunkel et al., 2013). Although some ingredients that are favourable for severe thunderstorms have increased over the years, others have not; thus, overall, changes in the frequency of environments favourable for severe thunderstorms have not been statistically significant... For hailstorms, such as those that caused disasters in the USA in 2018, detection of the role of climate change in changing hail storms is more difficult, because hail storms are not, in general, directly simulated by convection-permitting models and not adequately represented by the environmental parameters of coarse-resolution GCMs (Mahoney, 2020).

In summary, it is extremely difficult to detect and attribute changes in severe convective storms. There is limited evidence that extreme precipitation associated with severe convective storms has increased in some cases.

8A.7 Hurricanes and Tropical Cyclones

SREX (p. 159):

There have been no significant trends observed in global tropical cyclone frequency records, including over the present 40-year period of satellite observations (e.g., Webster et al., 2005). Regional trends in tropical cyclone frequency have been identified in the North Atlantic, but the fidelity of these trends is debated (Holland and Webster, 2007; Landsea, 2007; Mann et al., 2007a). Different methods for estimating undercounts in the earlier part of the North Atlantic tropical cyclone record provide mixed conclusions (Chang and Guo, 2007; Mann et al., 2007b; Kunkel et al., 2008; Vecchi and Knutson, 2008). Regional trends have not been detected in other oceans (Chan and Xu, 2009; Kubota and Chan, 2009; Callaghan and Power, 2011). **It thus remains uncertain whether any observed increases in tropical cyclone frequency on time scales longer than about 40 years are robust,** after accounting for past changes in observing capabilities (Knutson et al., 2010).

AR5 (pp. 216-17):

Current data sets indicate no significant observed trends in global tropical cyclone frequency over the past century and it remains uncertain whether any reported long-term increases in tropical cyclone frequency are robust, after accounting for past changes in observing capabilities (Knutson et al., 2010). **No robust trends in annual numbers of tropical storms, hurricanes and major hurricanes counts have been identified** over the past 100 years in the North Atlantic basin. Measures of land-falling tropical cyclone frequency (Figure 2.34) are generally considered to be more reliable than counts of all storms which tend to be strongly influenced by those that are weak and/or short lived. Callaghan and Power (2011) find a statistically significant decrease in Eastern Australia land-falling tropical cyclones since the late 19th century although including 2010/2011 season data this trend becomes non-significant (i.e., a trend of zero lies just inside the 90% confidence interval). Significant trends are not found in other oceans on shorter time scales (Chan and Xu, 2009; Kubota and Chan, 2009; Mohapatra et al., 2011; Weinkle et al., 2012), although Grinsted et al. (2012) find a significant positive trend in eastern USA using tide-gauge data from 1923–2008 as a proxy for storm surges associated with land-falling hurricanes. Differences between tropical cyclone studies highlight the challenges that still lie ahead in assessing long-term trends.

In summary, this assessment does not revise the SREX conclusion of *low confidence* that any reported long-term (centennial) increases in tropical cyclone activity are robust, after accounting for past changes in observing capabilities. More recent assessments indicate that **it is unlikely that annual numbers of tropical storms, hurricanes and major hurricanes counts have increased over the past 100 years in the North Atlantic basin.** Evidence, however, is for a virtually certain increase in the frequency and intensity of the strongest tropical cyclones since the 1970s in that region.

AR6 (p. 1585)

There is low confidence in most reported long-term (multidecadal to centennial) trends in TC frequency- or intensity-based metrics due to changes in the technology used to collect the best-track data. This should not be interpreted as implying that no physical (real) trends exist, but rather as indicating that either the quality or the temporal length of the data is not adequate to provide robust trend detection statements, particularly in the presence of multidecadal variability.

There are previous and ongoing efforts to homogenize the best-track data (Elsner et al., 2008; Kossin et al., 2013, 2020; Choy et al., 2015; Landsea, 2015; Emanuel et al., 2018) and there is substantial literature that finds positive trends in intensity-related metrics in the best-track during the “satellite period”, which is generally limited to the past ~40 years (Kang and Elsner, 2012; Kishtawal et al., 2012; Kossin et al., 2013, 2020; Mei and Xie, 2016; Zhao et al., 2018; Tauvale and Tsuboki, 2019). **When best-track trends are tested using homogenized data, the intensity trends generally remain positive, but are smaller in amplitude** (Kossin et al., 2013; Holland and Bruyère, 2014). **Kossin et al. (2020) extended the homogenized TC intensity record to the period 1979–2017 and identified significant global increases in major TC exceedance probability of about 6% per decade.** In addition to trends in TC intensity, there is evidence that TC intensification rates and the frequency of rapid intensification events have increased within the satellite era (Kishtawal et al. 2012; Balaguru et al., 2018; Bhatia et al., 2018). The increase in intensification rates is found in the best-track as well as the homogenized intensity data.

A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows no trend in the frequency of U.S. landfall events (Knutson et al., 2019).

Note: The **Underlined** text referenced a study (Kossin et al. 2020) that later retracted a portion of its findings. The authors assembled a data set on global TC incidence spanning 1979 to 2017. They claimed that the global fraction of TCs reaching major status (Cat 3–5) rose from 27% in the 1979–1997 interval to 31% in the 1998–2017 interval and the difference was statistically significant. Closer examination of their results however showed a significant increase was only observed in the North Atlantic (18% to 34%) whereas in every other basin (Eastern Pacific, Western Pacific, North Indian, South Indian, South Pacific) the differences were not statistically significant. Kossin et al. issued a Correction (<https://www.pnas.org/doi/10.1073/pnas.2021573117>). The revised version said that the global probability of observing a major TC was 34% in the 1979 to 1997 interval rising to 37% in the later period and the evidence for statistical significance was now weaker, although the authors claimed that the correction did not affect their conclusions.

8A.8 Droughts

US NCA17 REPORT (Ch. 8, Wehner et al. 2017)

p. 231:

Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (very high confidence). **While by some measures drought has decreased over much of the continental United States in association with long-term increases in precipitation, neither the precipitation increases nor inferred drought decreases have been confidently attributed to anthropogenic forcing.**

The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human

influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures. (*High confidence*)

p. 233:

Drought is, of course, directly connected to seasonal precipitation totals. Figure 7.1 shows detectable observed recent changes in seasonal precipitation. In fact, the increases in observed summer and fall precipitation are at odds with the projections in Figure 7.5. **As a consequence of this increased precipitation, drought statistics over the entire CONUS have declined.**

SREX (p. 170)

From a paleoclimate perspective recent droughts are not unprecedented, with severe ‘megadroughts’ reported in the paleoclimatic record for Europe, North America, and Australia (Jansen et al., 2007). Recent studies extend this observation to African and Indian droughts (Sinha et al., 2007; Shanahan et al., 2009): much more severe and longer droughts occurred in the past centuries with widespread ecological, political, and socioeconomic consequences. Overall, these studies confirm that in the last millennium several extreme droughts have occurred (Breda and Badeau, 2008; Kallis, 2008; Büntgen et al., 2010).

In North America, there is *medium confidence* that there has been an overall slight tendency toward less dryness (wetting trend with more soil moisture and runoff; Table 3-2), although analyses for some subregions also indicate tendencies toward increasing dryness. This assessment is based on several lines of evidence, including simulations with different hydrological models as well as PDSI and CDD estimates (Alexander et al., 2006; Andreadis and Lettenmaier, 2006; van der Schrier et al., 2006a; Kunkel et al., 2008; Sheffield and Wood, 2008a; Dai, 2011).

The most severe droughts in the 20th century have occurred in the 1930s and 1950s, where the 1930s Dust Bowl was most intense and the 1950s drought most persistent (Andreadis et al., 2005) in the United States, while in Mexico the 1950s and late 1990s were the driest periods. Recent regional trends toward more severe drought conditions were identified over southern and western Canada, Alaska, and Mexico, with subregional exceptions (Dai, 2011).

SREX (p. 172)

Overall, though new studies have furthered the understanding of the mechanisms leading to drought, there is still relatively limited evidence to provide an attribution of observed changes, in particular given the issues associated with the availability of observational data (Section 3.2.1) and the definition and computation of drought indicators (Box 3-3). This latter point was mostly identified in post-AR4 studies (Box 3-3). Moreover, regions where consistent increases in drought are identified (see ‘Observed Changes’) are only partly consistent with those where projections indicate an enhancement of drought conditions in coming decades (see next paragraphs). We thus assess that there is *medium confidence* (see also Section 3.1.5) that anthropogenic influence has contributed to some changes in the drought patterns observed in the second half of the 20th century, based on its attributed impact on precipitation and temperature changes (though temperature can only be indirectly related to drought trends; see Box 3-3). However **there is *low confidence* in the attribution of changes in droughts at the level of individual regions.**

AR5 (pp. 214-215)

Based on evidence since AR4, SREX concluded that there were not enough direct observations of dryness to suggest high confidence in observed trends globally, although there was *medium confidence* that since the 1950s some regions of the world have experienced more intense and longer droughts. The differences between AR4 and SREX are due primarily to analyses post-AR4, differences in how both assessments considered drought and updated IPCC uncertainty guidance.

Because drought is a complex variable and can at best be incompletely represented by commonly used drought indices, discrepancies in the interpretation of changes can result. For example, Sheffield and Wood (2008) found decreasing trends in the duration, intensity and severity of drought globally. Conversely, Dai (2011a,b) found a general global increase in drought, although with substantial regional variation and individual events dominating trend signatures in some regions (e.g., the 1970s prolonged Sahel drought and the 1930s drought in the USA and Canadian Prairies). Studies subsequent to these continue to provide somewhat different conclusions on trends in global droughts and/or dryness since the middle of the 20th century (Sheffield et al., 2012; Dai, 2013; Donat et al., 2013c; van der Schrier et al., 2013).

In summary, the current assessment concludes that there is not enough evidence at present to suggest more than *low confidence* in a global-scale observed trend in drought or dryness (lack of rainfall) since the middle of the 20th century, owing to lack of direct observations, geographical inconsistencies in the trends, and dependencies of inferred trends on the index choice. Based on updated studies, AR4 conclusions regarding global increasing trends in drought since the 1970s were probably overstated. However, it is *likely* that the frequency and intensity of drought has increased in the Mediterranean and West Africa and decreased in central North America and north-west Australia since 1950.

AR6 (Drought, Observed trends, Section 11.6.2, pp. 1573-75)

p. 1573

Strong precipitation deficits have been recorded in recent decades in the Amazon (2005, 2010), south-western China (2009–2010), south-western North America (2011–2014), Australia (1997–2009), California (2014), the middle East (2012–2016), Chile (2010–2015), the Great Horn of Africa (2011), among others (van Dijk et al., 2013; Mann and Gleick, 2015; Rowell et al., 2015; Marengo and Espinoza, 2016; Dai and Zhao, 2017; Garreaud et al., 2017, 2020; Marengo et al., 2017; Brito et al., 2018; Cook et al., 2018). **Global studies generally show no significant trends in SPI time series** (Orlowsky and Seneviratne, 2013; Spinoni et al., 2014), **and in derived drought frequency and severity data** (Spinoni et al., 2019), with very few regional exceptions (Section 11.9 and Figure 11.17).

p. 1574

For AR6 regions, several studies suggest an increase in the frequency and areal extent of soil moisture deficits, with examples in East Asia (Cheng et al., 2015; Y. Qin et al., 2015; Jia et al., 2018), Western and Central Europe (Trnka et al., 2015b), and the Mediterranean (Hanel et al., 2018; Moravec et al., 2019; Markonis et al., 2021). **Nonetheless, some analyses also show no long-term trends in soil drying in some AR6 regions – for example, in Eastern North America (Park Williams et al., 2017) and Central North America (Seager et al., 2019), as well as in North Eastern Africa (Kew et al., 2021).**

There is evidence based on streamflow records of increased hydrological droughts in East Asia (D. Zhang et al., 2018) and southern Africa (Gudmundsson et al., 2019). **In areas of Western and Central Europe and Northern Europe, there is no evidence of changes in the severity of hydrological droughts since 1950** based on flow reconstructions (Caillouet et al., 2017; Barker et al., 2019) and observations (Vicente-Serrano et al., 2019). **In North America, depending on the methods, datasets and study periods, there are differences between studies that suggest an increase (Shukla et al., 2015; Udall and Overpeck, 2017) versus a decrease in hydrological drought frequency (Mo and Lettenmaier, 2018), but in general there is strong spatial variability** (Poshtiri and Pal, 2016). Streamflow observation reference networks of near-natural catchments have also been used to isolate the effect of climate trends on hydrological drought trends in a few regions, but these show limited trends in Northern Europe and Western and Central Europe (Stahl et al., 2010; Bard et al., 2015; Harrigan et al., 2018), North America (Dudley et al., 2020) and most of Australia, with the exception of Eastern and Southern Australia (X.S. Zhang et al., 2016).

p. 1575

Few AR6 regions show observed increases in meteorological drought (Section 11.9), mostly in Africa and South America (NES: *high confidence*; WAF, CAF, ESAF, SAM, SWS, SSA, SAS: *medium confidence*); a few others show a decrease (WSB, ESB, NAU, CAU, NEU, CNA: *medium confidence*). There are stronger signals indicating observed increases in agricultural and ecological drought (Section 11.9), which highlights the role of increased [evapotranspiration], driven by increased [Atmospheric Evaporative Demand], for these trends (Sections 11.6.2.3, 11.6.2.5). Past increases in agricultural and ecological droughts are found on all continents and several regions (WAF, CAF, WSAF, ESAF, WCA, ECA, EAS, SAU, MED, WCE, NES: *medium confidence*), while decreases are found only in one AR6 region (NAU: *medium confidence*). The more limited availability of datasets makes it more difficult to assess historical trends in hydrological drought at regional scale (Section 11.9). Increasing (MED: *high confidence*; WAF, EAS, SAU: *medium confidence*) and decreasing (NEU, SES: *medium confidence*) trends in hydrological droughts have only been observed in a few regions.

AR6 on Attribution (p. 1577)

There are only two AR6 regions in which there is at least *medium confidence* that human-induced climate change has contributed to changes in meteorological droughts (Section 11.9). In South-western South America (SSW), there is *medium confidence* that human-induced climate change has contributed to an increase in meteorological droughts (Boisier et al., 2016; Garreaud et al., 2020), while in Northern Europe (NEU), there is *medium confidence* that it has contributed to a decrease in meteorological droughts (Gudmundsson and Seneviratne, 2016) (Section 11.9). **In other AR6 regions, there is inconclusive evidence in the attribution of long-term trends, but a human contribution to single meteorological events or subregional trends has been identified in some instances... In North America, the human influence on precipitation deficits is complex (Wehner et al., 2017), with low confidence in the attribution of long-term changes in meteorological drought in AR6 regions.**

From: Judith Curry <curry.judith@gmail.com>
Sent: Tuesday, May 6, 2025 1:24 PM
To: Ross McKittrick
Cc: John Christy; Roy W. Spencer; Travis Fisher; Steven Koonin
Subject: Re: Ch 8 Extreme weather

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John C.

Sent from my iPhone

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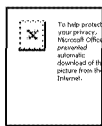
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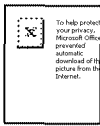
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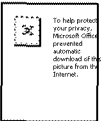
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Ross



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From: John Christy <climateman60@gmail.com>
Sent: Tuesday, May 6, 2025 4:20 PM
To: Judith Curry
Cc: Ross McKittrick; Roy W. Spencer; Travis Fisher; Steven Koonin
Subject: Re: Ch 8 Extreme weather

Ross and Judy

I'll do a makeover of chapter 8 and make a clean copy. Judy - if you put something in a section 3, that would be great.

Ross: Yes in 1899 the average station had 4 daily cold records (the Valentine's Day event was massive), some had 20 but some had none. Recall for the cold season, each station must contribute 122 values to the whole 126-yr time series. The "expected value" would be 0.96 average per station, so an extreme value of 4 for the CONUS is OK.

I like the LTP addition.

I'll redo the frequency-of-heavy-events charts as grand totals only, but I'll miss the colorful information.

Heatwaves: NCA5 used 6-days @90%tile rather than 7 that I used. I can redo to match (won't change the numbers).

John C.

John Christy
Director, Earth System Science Center
Professor, Atmos and Earth Science
Alabama State Climatologist
The University of Alabama in Huntsville
climateman60@gmail.com

On May 6, 2025, at 1:20 PM, Judith Curry <curry.judith@gmail.com> wrote:

ok, we can have section 3 on "other", which is mainly a few graphs and a para for each graph

On Tue, May 6, 2025 at 11:00 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

But we also need to discuss landfalling hurricanes, drought, wildfires, tornadoes, etc. Even if just focused on the US.

On Tue, May 6, 2025 at 1:24 PM Judith Curry <curry.judith@gmail.com> wrote:

I vote to keep Ch 8 focused only on US weather and climate extremes. Since this doc is to support US policy making and the IPCC is out there as a ref for global extremes. Ch 8 fixes a huge deficiency in the NCA reports: they didn't look at a long enough time series of data

On Tue, May 6, 2025 at 10:04 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:
Here's another edition of Ch 8 on extremes taking Judy's and John's points into account. The IPCC/NCA review is ported to an Appendix. I added a paragraph about LTP to the intro. I've incorporated the NE data. The bulk of the chapter is John's US temperature and precip data analysis with some additional material on wildfires, drought and TCs. For the US temperature extremes I moved the range figure to come just after the hot/cold extremes count because I think they both make a coherent point namely that the US becoming less extreme because heat events are rising more slowly than cold events are warming. There will still need to be an overall chapter summary but I'm going to move on to other chapters now. I'll put this in the Dropbox.

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All

We can fill in without much trouble the change, or lack thereof, of “high impact” weather events (mainly wind and flooding like hurricanes, tornadoes etc) in the CONUS Extreme chapter. The temp and precip metrics are important because they are just long enough to essentially tell us Mother Nature has a mind of her own.

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2. We have analyses of the CONUS with more complete datasets than the NCA used (recall NCA analyses depended essentially on a small group at NCEI using datasets that (a) were not very consistent in time, (b) could promote alarm and (c) already easy for them to get to. Our datasets have literally hundreds of thousands of manually keyed-in observations for temporal consistency. In other words, this lets people know we can address these issues from soup to nuts - we're not armchair climate scientists ... we can reproduce what they did, but make the analysis more comprehensive to address the questions.

John C.

Sent from my iPhone

On May 6, 2025, at 4:14 AM, Ross McKittrick

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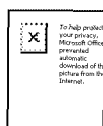
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Ross

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Judith Curry, President

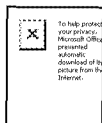
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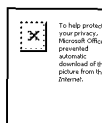
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From: John Christy <climateman60@gmail.com>
Sent: Tuesday, May 6, 2025 6:26 PM
To: Ross McKittrick
Cc: Steve Koonin; Judith Curry; Roy W. Spencer; Travis Fisher
Subject: Re: Ch 8 Extreme weather

Steve

As Ross notes, the precipitation section is simply an update of our 2019 paper. The daily temperature work from the supplemented USHCN records is in a paper under review (but I suspect will have difficulty being accepted). The data are from the official USHCN site with my supplements adding about 10 percent to cover the missing data. There are about 41 million temperatures here, so I added about 4 million. Thus the results are dominated by publically-available data for others to check. If I get the go-ahead for publication, I can put the complete datafiles on a server for anyone to use.

John C.

John Christy
Director, Earth System Science Center
Professor, Atmos and Earth Science
Alabama State Climatologist
The University of Alabama in Huntsville
climateman60@gmail.com

On May 6, 2025, at 3:48 PM, Ross McKittrick <ross.mckittrick@gmail.com> wrote:

The underlying analysis is all from John's and my Journal of Hydrology paper for which the code is already online. John updated and expanded the data sets and I ran them through the same code.

On Tue, May 6, 2025 at 4:41 PM Steven Koonin <steven.koonin@gmail.com> wrote:

A thought about the analysis of long-term CONUS data, which as John knows I like very much:

If some (most?) of this work is as-yet unpublished in a peer-reviewed journal, I'd think you've got to make the expanded and in-filled database (and analysis code?) publicly accessible so that the work can be checked. Are you prepared to do that (at least for the "final", if not the "draft")?

SEK

From: Ross McKittrick <ross.mckittrick@gmail.com>
Sent: Tuesday, May 6, 2025 1:05 PM
To: John Christy <climateman60@gmail.com>
Cc: Judith Curry <curry.judith@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Steven Koonin <steven.koonin@googlemail.com>
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From: John Christy [climateman60@gmail.com]
Sent: 5/7/2025 1:53:06 AM
To: Ross McKittrick [ross.mckittrick@gmail.com]
CC: Steve Koonin [steven.koonin@gmail.com]; Judith Curry [curry.judith@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]
Subject: Re: Ch 8 Extreme weather
Attachments: 8 Extreme weather.JRC.May07.docx; Untitled attachment 01982.htm

All

Here is a cleaned up version of chapter 8 which you will likely not see until 7 May, so that is the date.

My preference is for someone to read the thing and write the summary (8.4) based upon what a fresh set of eyes would conclude. Steve? Roy?

Ross. The panel charts of the individual station precipitation take up a lot of real estate and I think the value per acre is low. Since you calculated 3 statistics for each station, could you craft a bar chart or something to show that result? You would then have 9 charts, one for each of the 3 statistics and one each of the three regions. The nine charts may be panelized and fit on one plot. I know for us it's important for people to see the actual data (which is why I had those colored bar charts - now monochromatic), but it may be overkill for this document.

As to one of the statistics, I believe 3-day totals will be more meaningful and accurate than 1-day totals. I could send you a file of the heaviest 3-day total for each station and each year and you can do the analysis from there.

I especially like the way you parsed the Sidebar and I hope smart people will finally understand that when dealing with climate, our sample is pathetically small from which to draw hard conclusions.

I also enjoyed the added words on LTP. In fact do you have a few sentences that expand that a little to talk about the erratic nature of precipitation (spatial and temporal) in fancy statistical terms which means finding statistical significance in such a variable is a tough job?

I redid the number-of-event bar charts - all one color now.

I reran the Heatwave results to use 6-day periods as did NCA5. NCA5 was slick though. By choosing 1961-90 their background climatology was cold relative to decades before and since, so that results outside of those 30 years would produce a lot of days that exceed the percentile threshold. Then in the urban heatwave website, they started in 1960, assuring a result that more temps would exceed the threshold in post-1990 years.

That's all I've got.

Aloha

John C.

John Christy
Director, Earth System Science Center
Professor, Atmos and Earth Science
Alabama State Climatologist
The University of Alabama in Huntsville

climateman60@gmail.com

8 Extreme weather in the US and elsewhere

8.1 Introduction

Weather extremes, usually related to temperature and/or precipitation, often disrupt infrastructure and therefore human health and thriveability. Indeed, the ability of any surface-dwelling species to live productively is somewhat constrained by these extremes which in essence create the bounding limits for survival. The issue here is whether these extremes, and their attendant potential danger, may be changing and if so whether the change is in response to increases in infrared-absorbing greenhouse gases (GHGs) (e.g., IPCC AR6 Seneviratne et al. 2021).

Unfortunately, the sample of time from which we are able to quantitatively analyze variations in extreme events is quite brief, around 130 years. This period certainly does not begin to contain all of the extreme events that the climate system is able to create naturally. Over geologic time the climate system has generated an (essentially) infinite variety of patterns and extremes which humans have never observed, and thus do not enter our databases from which extreme statistics are determined [see *Perils of short data records* below]. Thus, assuming that a climate pattern or event hitherto not experienced in our lifetime must therefore be the result of enhanced GHG concentrations requires the assumption that natural variations are insignificant.

This is especially true for precipitation events. The hydrological literature has long noted the phenomenon of *Long Term Persistence* (LTP) in rainfall data (Hurst 1951, Cohn and Lins 2005, Markonis and Koutsoyiannis 2015). LTP has a formal mathematical definition but it can be thought of intuitively as the presence of natural variations with strong autocorrelation properties that result in cycle-like behavior on long time scales. The presence of LTP requires very long data samples to obtain accurate estimates of variance; analysis of data samples that are short relative to the LTP scale will tend to yield underestimated variances which in turn yields overstated significance of apparent trends and underestimation of the likelihood of extreme events (Cohn and Lins 2005).

With this caveat in mind we examine the evidence for changes in weather and climate extremes. It has become routine in media discussions, government and private sector discussions and even in some academic literature to make generalized assertions that extreme weather of all types is getting worse due to GHGs and climate change. Yet expert assessments have not typically drawn such sweeping conclusions and instead have emphasized the difficulty both of identifying specific trends and establishing a causal connection with anthropogenic forcing. In the Appendix to this chapter we provide excerpts of these findings from previous IPCC and NCA assessments.

8.2 Global and continental indicators of extreme weather trends

8.2.1 Tropical Cyclones (TCs)

Hurricane strength records for the North Atlantic and the Western Pacific go back to 1950 and the record does not show an increase in either total or major TCs. Figure 8.1 was published by Roger Pielke Jr. as an update to the Best Track data series originally presented in Weinkle et al. (2012).

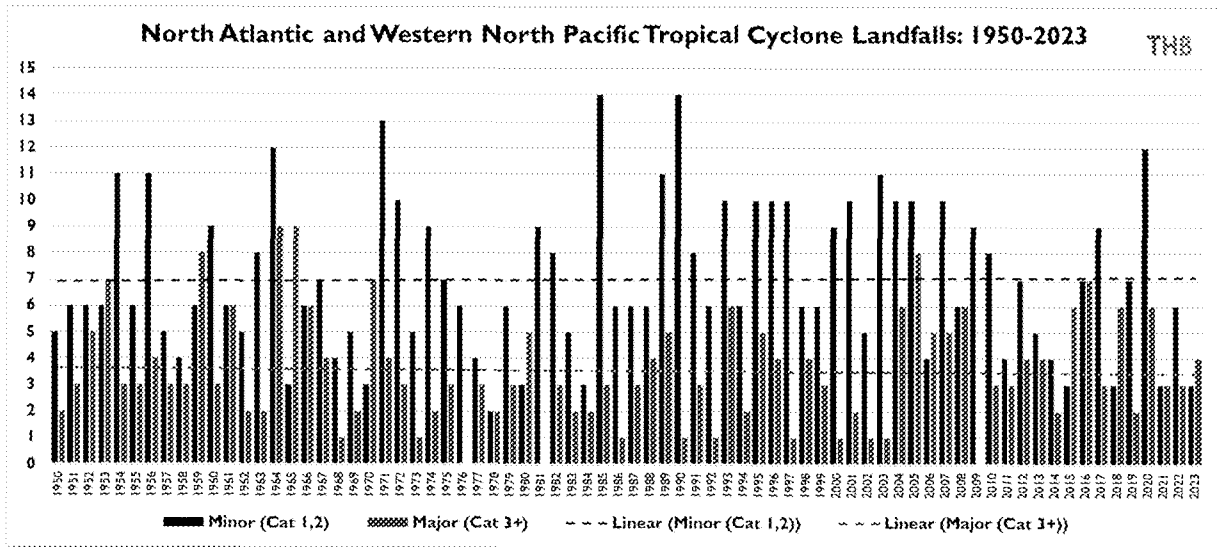


Figure 8.1. Tropical Cyclone Landfalls. Source: <https://rogerpielkejr.substack.com/p/global-tropical-cyclones>, Weinkle et al. (2012)

After 1980, as shown in Figure 8.2, which reproduces data from the Climate Atlas of Dr. Ryan Maue neither the total number of hurricanes nor the frequency of major ones have become more common since 1980, indeed both have trended down since the 1990s:

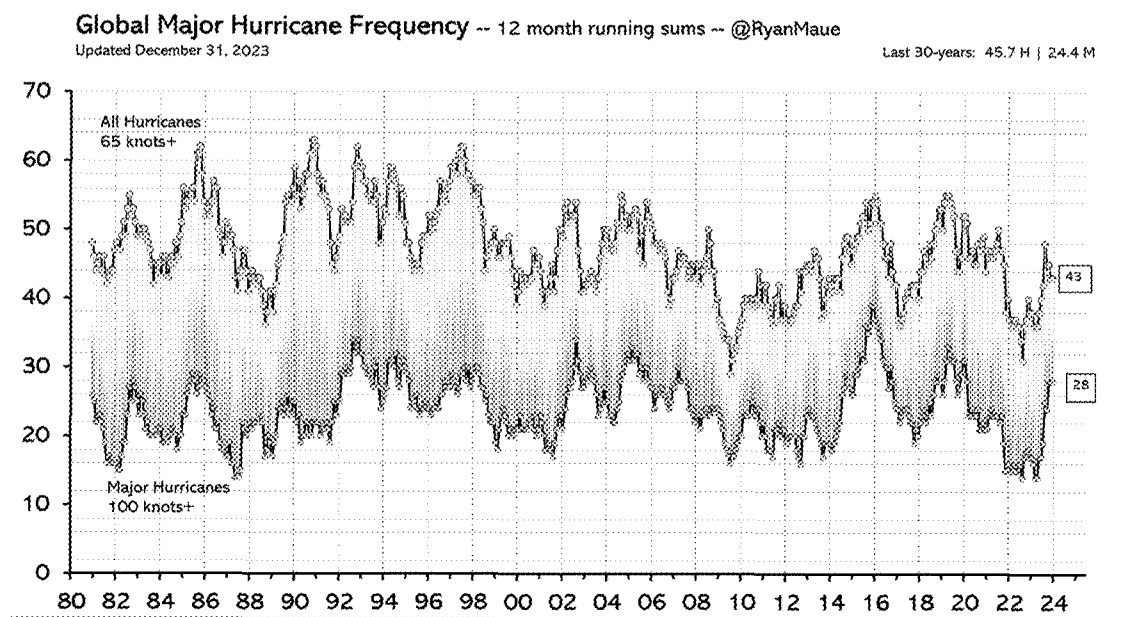


Figure 8.2: Global hurricane frequency. Source: Maue (2024)

A metric that combines the number and frequency of TCs is the Accumulated Cyclone Energy or ACE Index maintained at Colorado State University, shown in Figure 8.3.

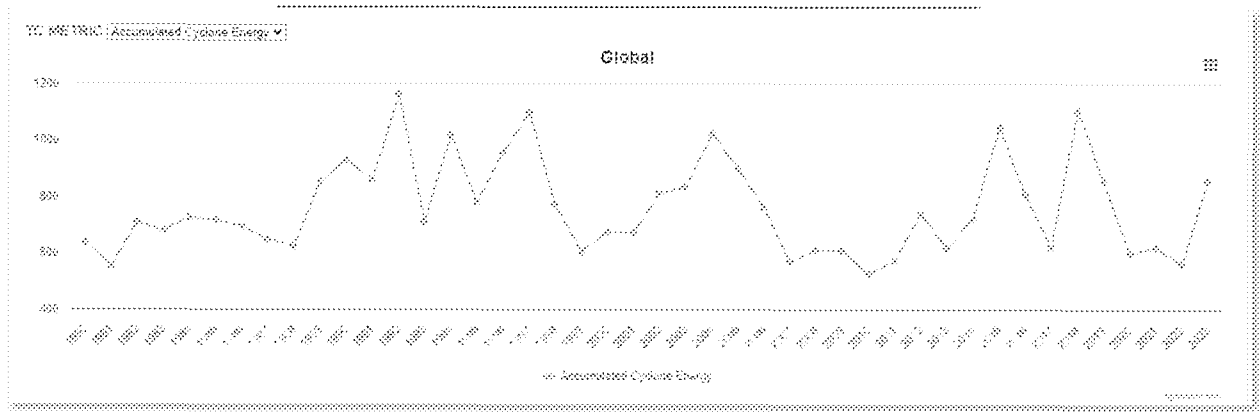


Figure 8.3: Global Accumulated Cyclone Energy. Source: Klotzbach (2025)
<https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=global>

As is clear, it is also not increasing and since 1990 has declined slightly.

Climate models project declining hurricane formation rates in a warming climate (Chand et al. 2022). Climate models also project fewer Tropical Cyclones under future global warming, and even though models project they will increase in strength, the annual averages of rainfall maxima decline (Stansfield et al. 2020). Note that Tu et al. (2024) report that the Power Dissipation Index (PDI), a measure of the destructiveness of hurricanes, has either remained unchanged or has declined in all global oceanic basins since the mid-1990s.

8.2.2 Wildfires

As shown in Figures 8.4 and 8.5 global wildfire activity as measured by European Space Agency peaked over a decade ago and shows a downward trend since.

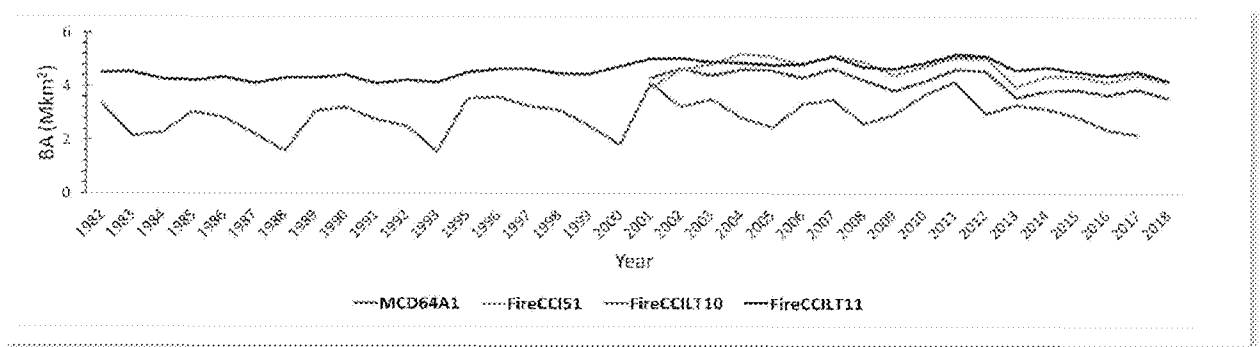


Figure 8.4: Global wildfire 1982-2018. Source: Copied from Oton et al. (2021). Note: the different coloured lines represent different data products based on satellites and algorithms used.

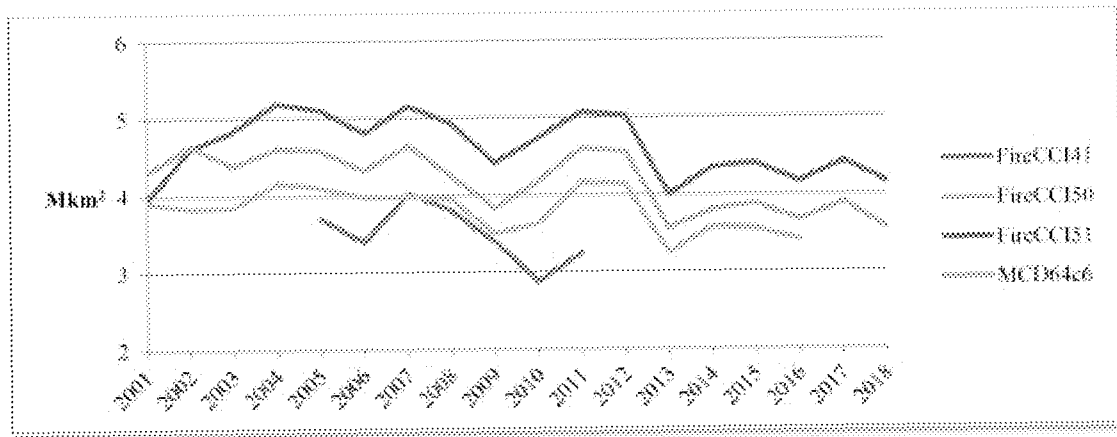


Figure 8.5: Global wildfire 2001-2018. Source: Copied from Lizundia-Loiola et al. (2021). Note: the different coloured lines represent different data products based on satellites and algorithms used

US data from the National Interagency Fire Centre (NIFC) from 1926 to 2023 are shown in Figure 8.6.

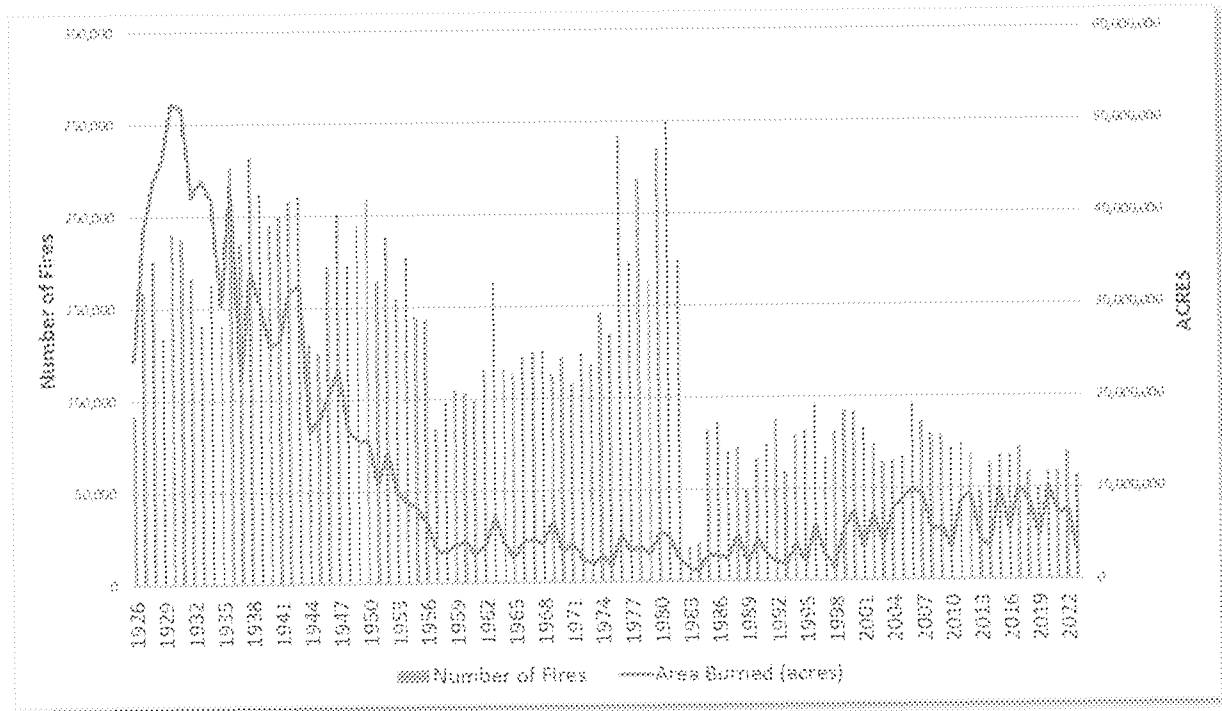


Figure 8.6: US wildfires 1926 to 2023. Source: National InterAgency Fire Centre data Pre-2017 (archived)

https://web.archive.org/web/20200212033452/https://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html. 2018-2023: <https://www.nifc.gov/fire-information/statistics/wildfires>

Note the NIFC has removed the pre-1960 data from its current website. They claim it is because measurement methods changed after 1960. This explanation seems inadequate since agencies blend temperature and extreme weather data series in other context when measurement systems changed. In this case if anything the measurement of wildfires has improved since the early 20th century so any bias will be towards understating early wildfire counts. Nonetheless just focusing on the post-

1985 interval the number of fires is not increasing. The area burned did increase but only until about 2007.

It is difficult to establish a natural baseline for wildfire activity because of active fire suppression activity since 1900. Paleoclimatic evidence indicates, however, that past wildfire activity was much higher than at present. Marlon et al. (2012) used sedimentary charcoal layers to reconstruct fire history of western US for the past 1400 years. They also fit a model to predict expected fire activity as a function of climatic conditions. The results are summarized in Figure 8.7 below (from Figure 2 in their paper).

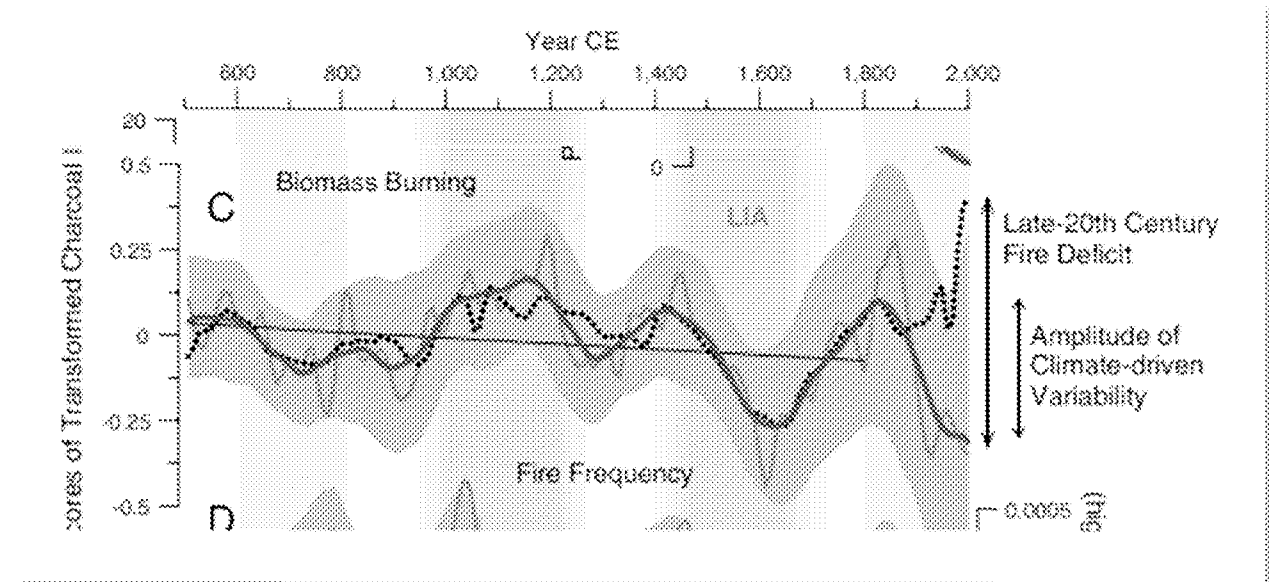


Figure 8.7: Fire frequency and fire deficit in the US. Source: Copied from Marlon et al. (2012)

In their figure the red line shows the smoothed charcoal record and the black dotted line shows the predicted charcoal record based on the statistical model. The gap at the end implies there has been a growing wildfire deficit over the 20th century. In other words, however much fire was observed in the 20th century it was less than what would have been observed in previous centuries based on the climatic conditions. Parks et al. (2025) likewise find that despite the recent increase in wildfire burn area in North America, relative to historical wildfire regimes there remains a significant wildfire deficit.

8.2.3 Precipitation

Figure 8.8 shows that US long term data from NOAA shows an insignificantly increasing tendency toward extreme wetness (+0.001% per year)

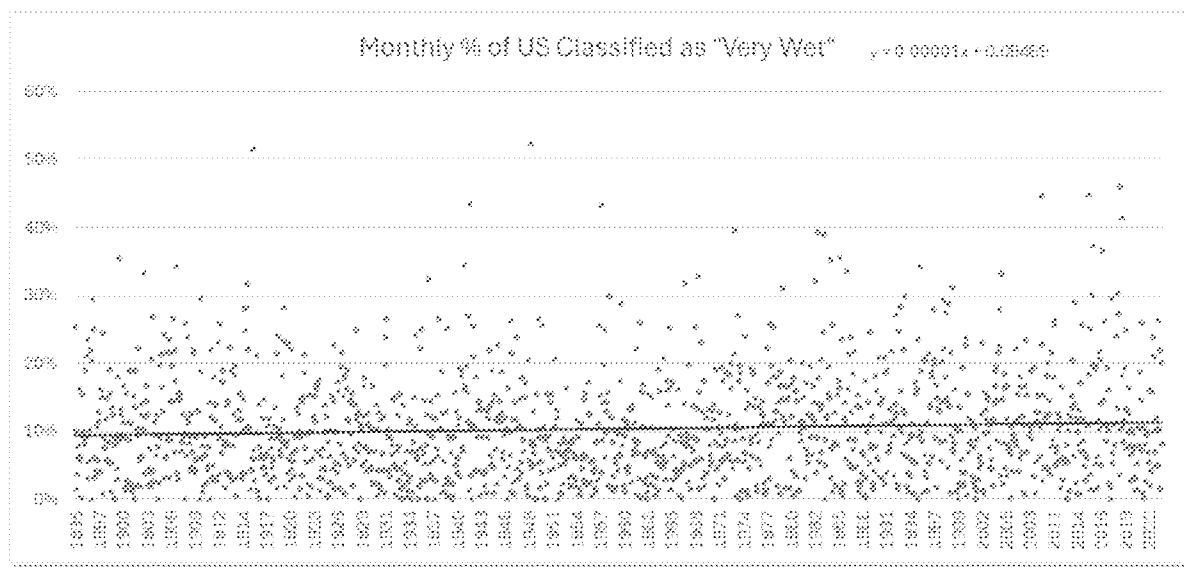


Figure 8.8: Long term US wetness (%). Source: NOAA
<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>

Precipitation will be discussed further in the review of CONUS data below.

8.2.4 Drought

As shown in Figure 8.9 US long term data (NOAA) shows an insignificantly declining tendency toward extreme dryness (-0.001% per year)

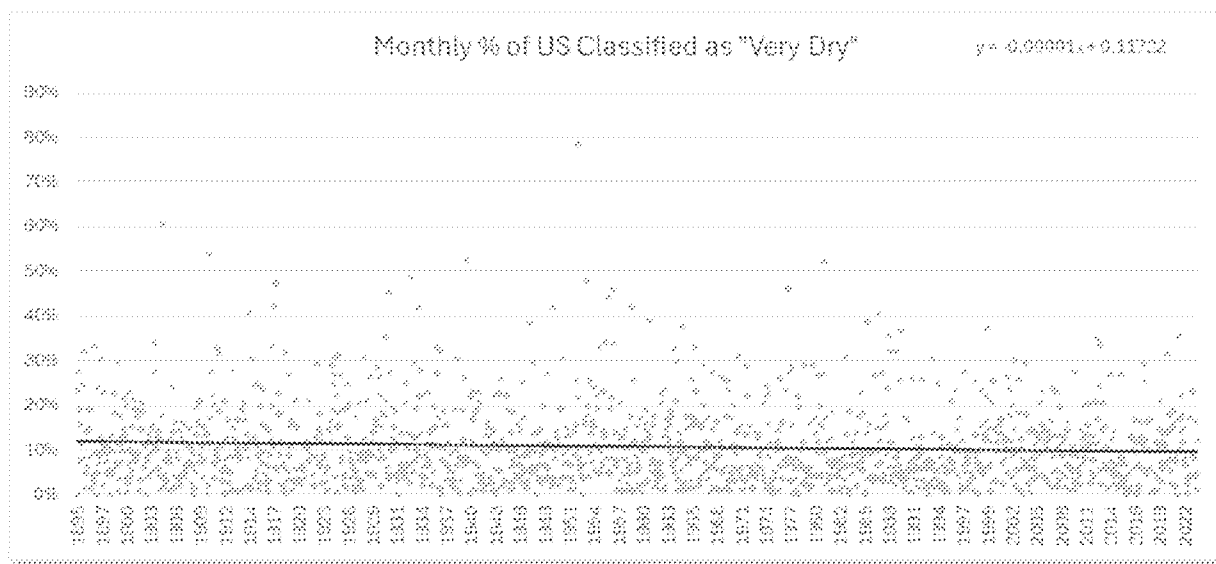


Figure 8.9: US dryness (%) 1895—2023. Source: NOAA
<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>

Kogan et al. (2020) examines a 38-year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change: “it is possible to state firmly that global and main grain countries’ drought area and intensity trends have not been following global climate warming since 1980’s.”

8.3 Analysis of Conterminous US (CONUS) data on temperature and precipitation extremes

8.3.1 CONUS daily temperatures are becoming less extreme

Daily maximum temperatures in the warm season (TMax, May-Sep) and daily minimum temperatures in the cold season (TMin, Dec-Mar) are available beginning in Dec 1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (Quinlan et al. 1987, Karl et al. 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although errors certainly reside in the dataset, with over 1,000 stations any underlying signal we discover-can be characterized by relatively high confidence.

We begin with the question of whether the occurrence of daily record high or low temperatures changed has changed since Dec 1898. Each warm-season has 153 days (1 May to 30 Sep) and each cold-season has 122 days (1 Dec to 31 Mar). For each station we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time-the expected number of records for TMax would be 1.21 per year and for TMin 0.96 per year. Figure 8.10 indicates the observed distribution in time of the occurrence of these extreme events.

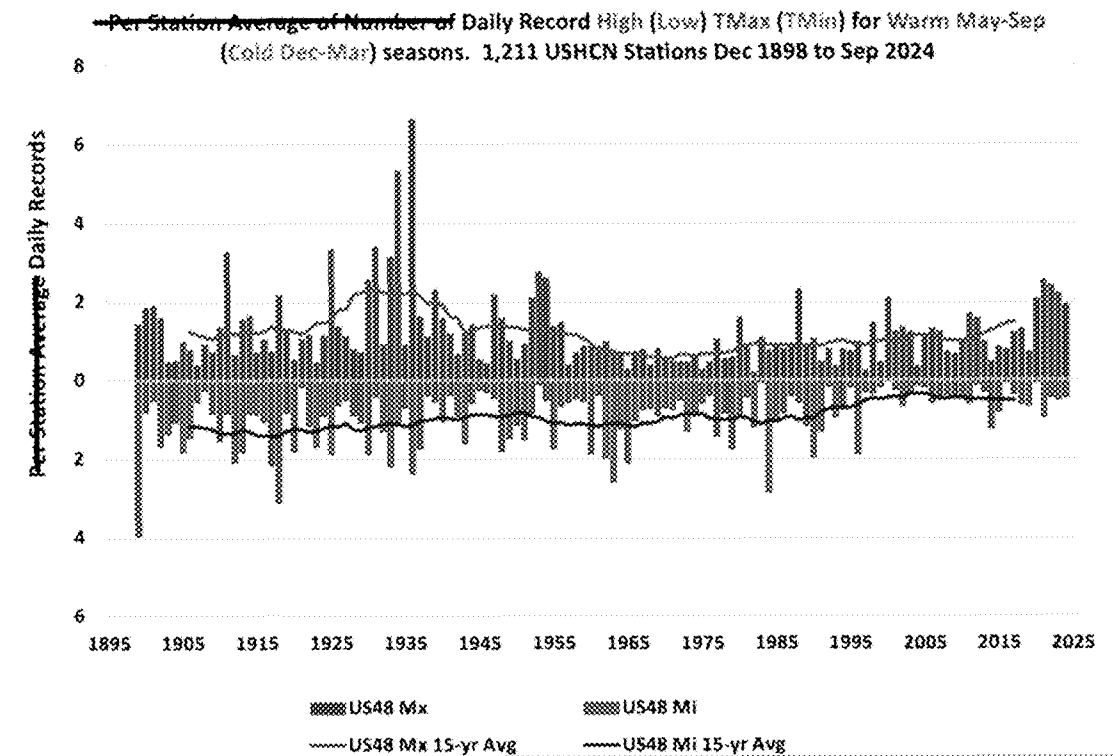


Figure 8.10 Number of daily record High (red) and Low (blue) for warm and cold seasons in the CONUS. The lines represent 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92% of observations in the 126-year period since Dec 1898.

The results indicate a common feature in many metrics of warm-season extremes in the CONUS - the exceptional heat of the 1920s and especially the 1930s peaking in 1936. On a per-station average, 60% of the TMax records and 59% of the TMin records occurred in the first half of the period (1899-1961).

On the cold side, the Valentine's Day Arctic outbreak in Feb 1899 stands as the most extensive cold extreme experienced by the CONUS, with 1917 2nd. The frequency of cold records has declined, especially over the last quarter of the period in which only 13% of the extreme cold events were measured. In contrast, 25% of the extreme TMax records were achieved in the last quarter in accordance with statistical expectations. These general features have been noted in past assessments (IPCC AR5, IPCC AR6, NCA4, NCA5). Combining the two records the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 8.11. For each station and for each year the hottest warm season and coldest cold-season temperatures were calculated and converted to anomalies relative to the station's long term warm and cold season (respectively) averages. Then the differences between these were computed by station and geographically-averaged over all stations, thus yielding an annual measure of the expected range of local extreme temperatures for each year. Figure 8.11 shows the 15-year trailing average of this measure which has clearly declined over the past century.

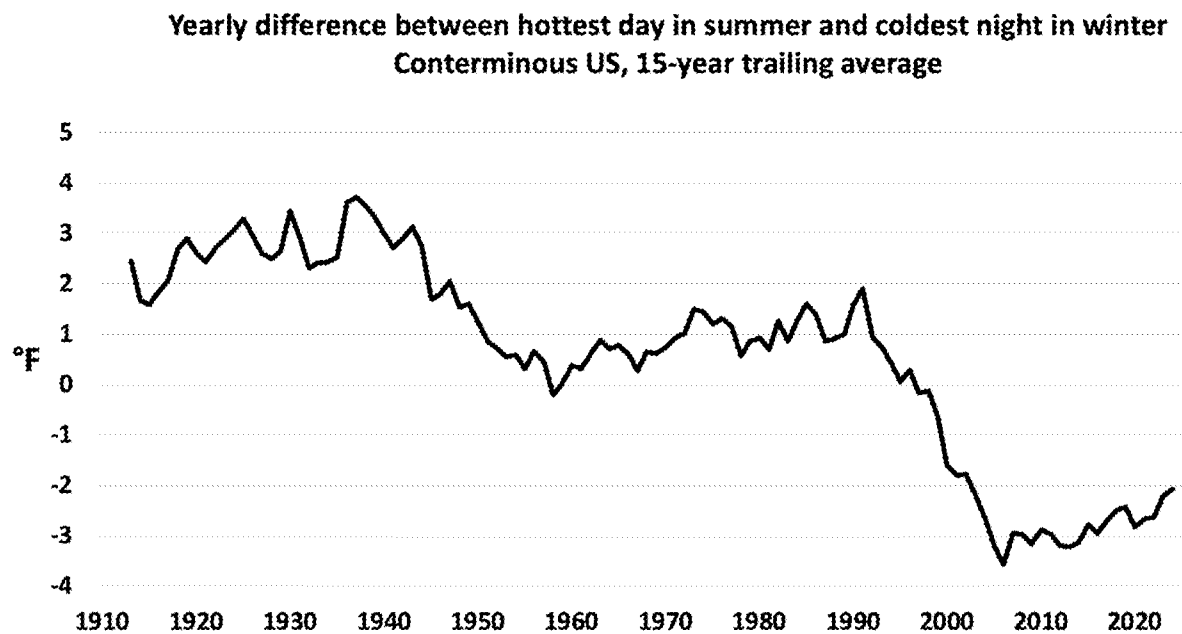


Figure 8.11. 15-year trailing average of the difference each year of each station’s hottest warm-season TMax and coldest cold-season TMin relative to the long-term average.

The average difference for each station between the hottest summer TMax and coldest winter TMin has declined about 5°F in the past 126 years. The decline is due mostly to warming winter TMin, but a decline in the magnitude of summer TMax is also a factor. The rise in TMin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (Spencer et al. 2025).

Summarizing Figures 8.10 and 8.11, while temperature extremes are regularly experienced in the US and attract a great deal of media attention, long term records show the US climate has become less extreme over time when measured in terms of the range between warm season maxima and cold season minima.

8.3.2 Exceedances of a heat threshold

Under the heading of “The Risk of Temperature Extremes is Changing”, the most recent US National Climate Assessment report (NCA5) notes the increase in a threshold metric of number of days at or above 95°F, stating,

“The western US has been particularly affected by extreme heat since the 1980s ..., experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021.”

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS, threshold statistics can be misleading. A region with many stations which have near 95°F TMax average

temperatures in the summer might see large swings in the metric when only small changes in average temperature occur. Elsewhere with stations that either rarely or virtually always achieve 95°F TMax temperatures, a small change will not impact the results much at all. In the past 126 years, the average CONUS station experienced 129 days exceeding 95°C per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, one needs to view such threshold analyses with caution.

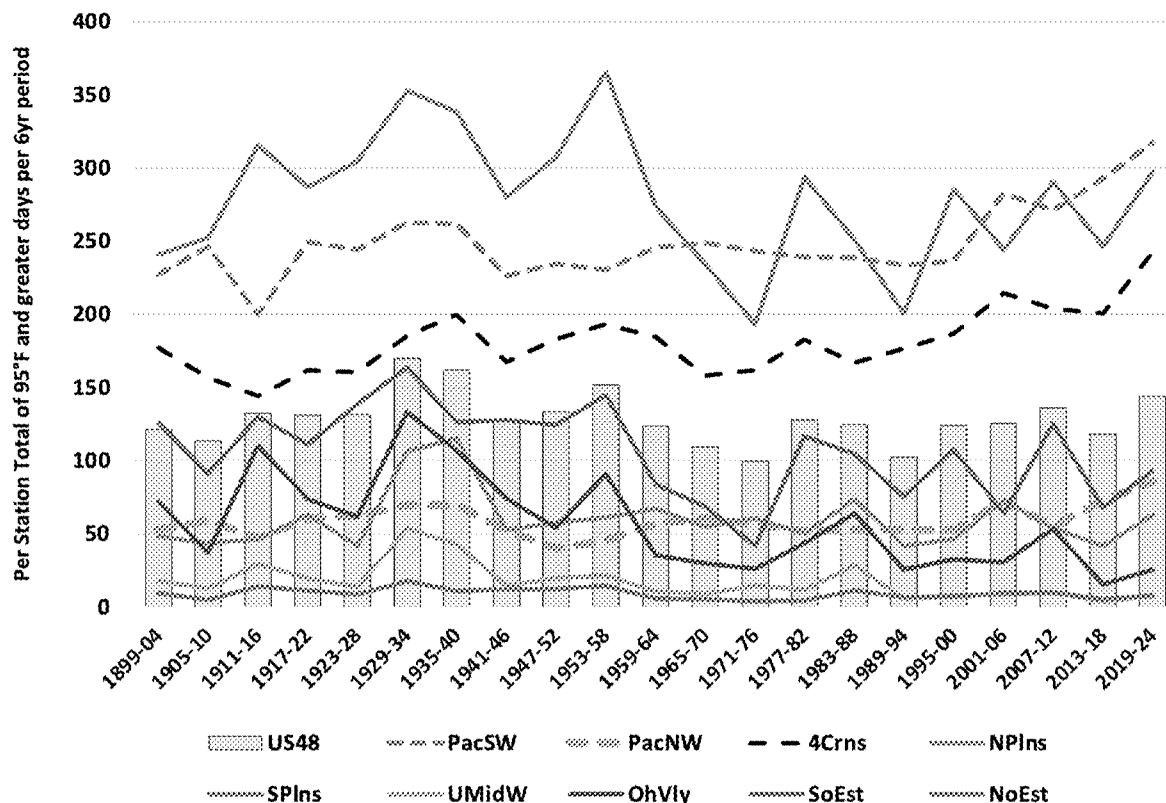


Figure 8.12. Total number of days $\geq 95^{\circ}\text{F}$ in 6-yr periods, US 48 (bars) and regions (lines).

In Fig. 8.12 we see that only three of the nine regions, all in the West, have experienced upward trends in the number of 95°F or hotter days (dashed lines). The CONUS as a whole has not and the other six regions have experienced declines.

The Pacific NW heatwave of 2021 is referenced as supportive information for the NCA5 claim, an event examined more closely in section 6.4. The evidence indicates it was a “black swan” event, i.e. a single, unprecedented event in the existing record suggesting it is not indicative of a pattern of increasing extreme heat. For example, the 5-day average tropospheric grid-point temperature anomaly over the Pacific NW was +10.8 C, the most extreme NH grid point summer anomaly in the 46 years from over 4 million grids. In contrast, the global anomaly was virtually zero (+0.03 C, Mass et al. 2024).

The heading “The Risk of Temperature Extremes is Changing” suggests positive trends are now being observed in threshold temperatures on a widespread basis, but that is not evidenced in the combined CONUS results of the figures above.

8.3.3 Heatwaves

Of more impact than a single daily record is the phenomena of heatwaves, or consecutive days which exceed an extreme threshold. For this study, the metric will be the number of “Heatwave Days” defined as the sum of all days in May-Sep each year which exceed the 90th percentile that occur within consecutive periods of at least six days in length. This is equivalent to the method in NCA5 except the reference period here is the entire record 1899-2024 while NCA5 limited the reference period to 1961-1990, a cool episode. By selecting 1961-1990, the occurrence of positive results (days exceeding the 90th percentile) will be enhanced in periods warmer than the reference base, especially if starting in 1960 and moving to the present (see *Urban Influences* below).

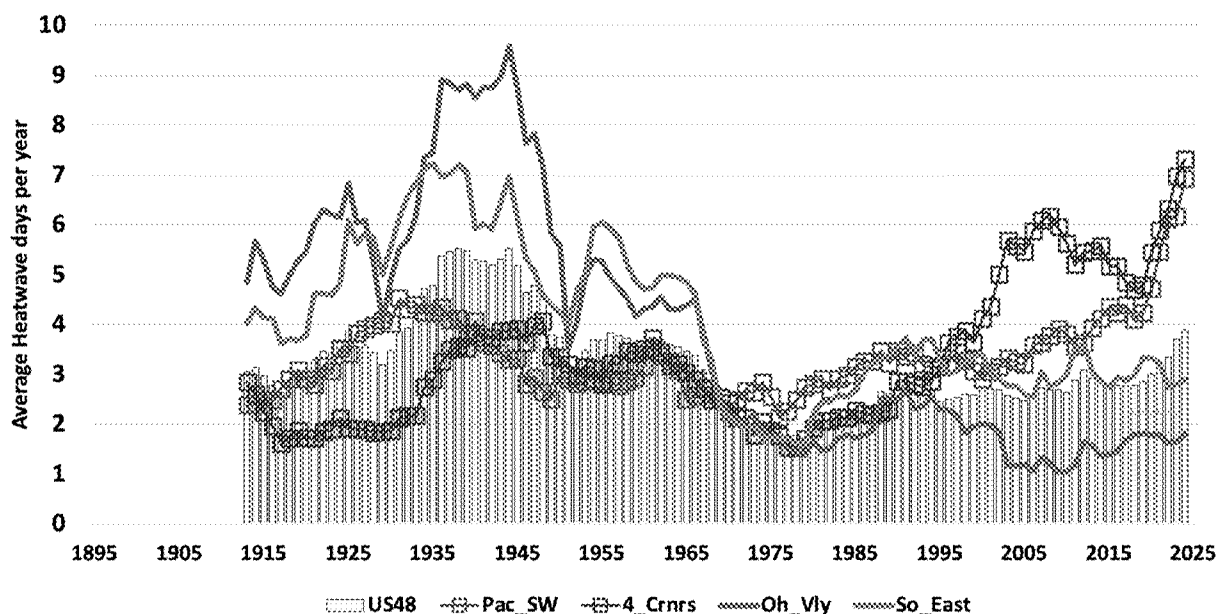


Figure 8.13 15-year trailing average of number of heatwave days per year per station in the CONUS (bars) and four regions: Pac_SW (purple squares, CA, NV), 4_Crnrs (red squares, AZ,NM,UT,CO), Oh_Vly (blue, MO, IL, KY, TN, IN, OH, WV) and So_East (green, MS, AL, GA, FL, SC, NC, VA).

Figure 8.13 indicates again the excessive heat of the first half of the 20th century, primarily in the eastern two-thirds of the nation, as seen in the regional values for the Ohio Valley and the Southeast as examples. The West has seen a recent increase of heatwave days and the two regions with the highest number are shown, the Pacific Southwest and the Four-Corners (NCA5). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20th century, but in the 21st century the patterns have favored heatwaves in the West.

Of interest here is the regional variation of this metric. The four northern regions (Pacific NW, Northern Plains, Upper Midwest, and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains,

Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

Urban influences

The NCA5 directs readers to the website <https://www.globalchange.gov/indicators/heat-waves> (USGCRP 2023) to view the number of urban heatwaves by decade from the 1960s. The figure reveals a monotonic increase in each decade from 2 occurrences per year in the 1960s to 6 in the 2020s. The definition of a heatwave is unusual but practical from a human discomfort perspective - a period of at least 2 consecutive days when the apparent minimum temperature (combination of temperature and humidity) exceeds the 85th percentile. Note too, the dataset is limited to the 50 largest cities in the US.

These increasing values since 1960 presented in USGCRP (2023) are entirely reasonable, but for at least two reasons unrelated to GHG emissions. Urbanization in these cities is a major factor in the rise of TMin relative to co-located TMax and relative to TMin at rural stations. Also, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. This does not dismiss the real rise in nighttime temperatures in major US cities and the societal impacts associated with these changes. However, we note for a variety of reasons, that summer TMax (especially in rural areas) serves as better response variable for detecting potential changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs (Christy et al. 2009). For the CONUS as a whole, the evidence in this section suggests GHG emissions have had little-to-no effect on heatwaves in the CONUS.

8.3.4 Extremes in daily precipitation.

Due to its stochastic and episodic character, precipitation requires careful statistical treatment to understand variability over long time periods (see *8.1 Introduction*). The US National Climate Assessments (NCA4, NCA5) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of the CONUS, especially the Northeast, when starting in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in extreme events are in the Northeast and least in the West, which is counter to the changes in temperature extremes shown above.

McKittrick and Christy (2019) examined long-term and consistent station observations of daily precipitation to test some of these NCA claims for the Southeast and West Coast. In neither case when the time series were extended back in time (as far as 1872 in some cases) or when starting later (1978) were the trends significant. For this report we update these findings with similarly constructed observations from 29 stations on the Pacific Coast (1893ff from San Diego CA to Blaine WA, see Figure 8.14), 24 stations in the humid Southeast (1872ff from Austin TX to Washington DC, see Figure 8.15), and 21 stations in the Northeast (1888ff from Buffalo NY to Gardiner ME, see Figure 8.16).

In the Pacific region, over the whole sample, the trend in average precipitation is negative and significant in Astoria and insignificant elsewhere. The trend in rainfall variance is positive and significant in Big Sur and insignificant elsewhere. The trend in daily maximum precipitation is positive and significant in Aberdeen and Big Sur and negative and significant in Newport and

insignificant elsewhere. Averaged over all stations in the region none of these three trend parameters is statistically significant.

In the Southeast region over the whole sample the trend in average precipitation is positive and significant only in Mobile and Quitman, the trend in rainfall variance is positive and significant only in Mobile and the trend in daily maximum precipitation is positive and significant only in Vicksburg and Norfolk. Averaged over all stations in the region none of these three trend parameters is statistically significant.

The Northeast region exhibits a pattern of increasing average rainfall. The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall. The trend in rainfall variance is positive and significant only in Portland, Albany and Buffalo and insignificant elsewhere and not in the regional average. The trend in daily maximum precipitation is positive and significant only in Portland ME and Gardiner ME and insignificant elsewhere and not in the regional average.

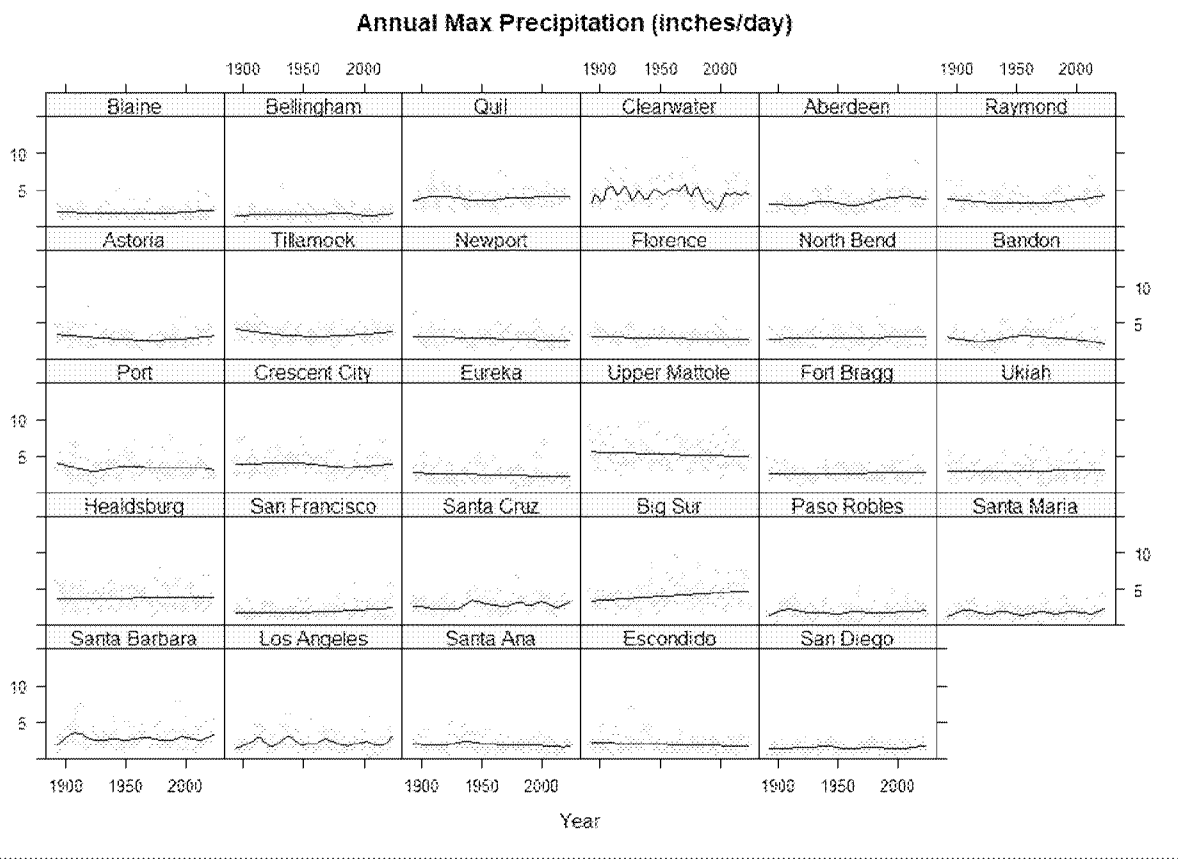


Figure 8.11 Annual maximum precipitation for 29 Pacific stations 1893 to present

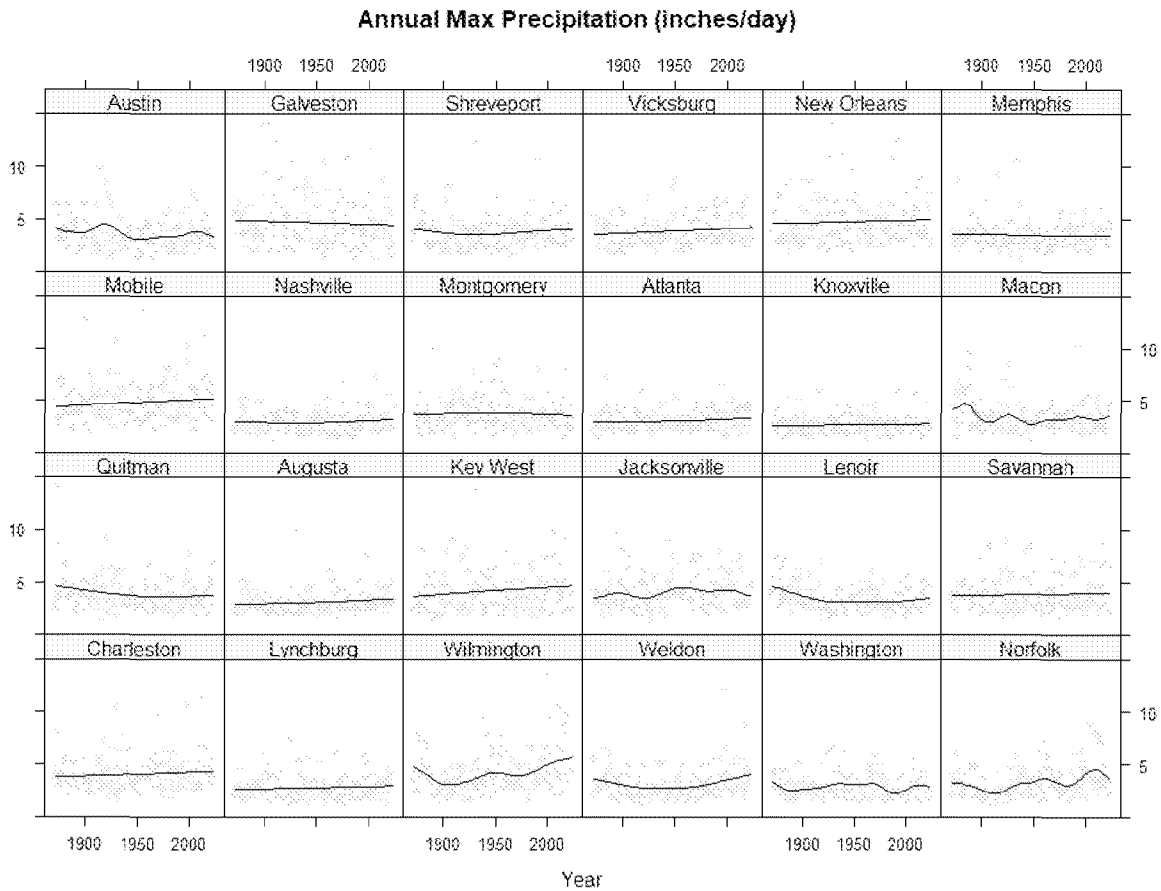


Figure 8.12 Annual maximum precipitation for 24 Southeast stations 1872 to present

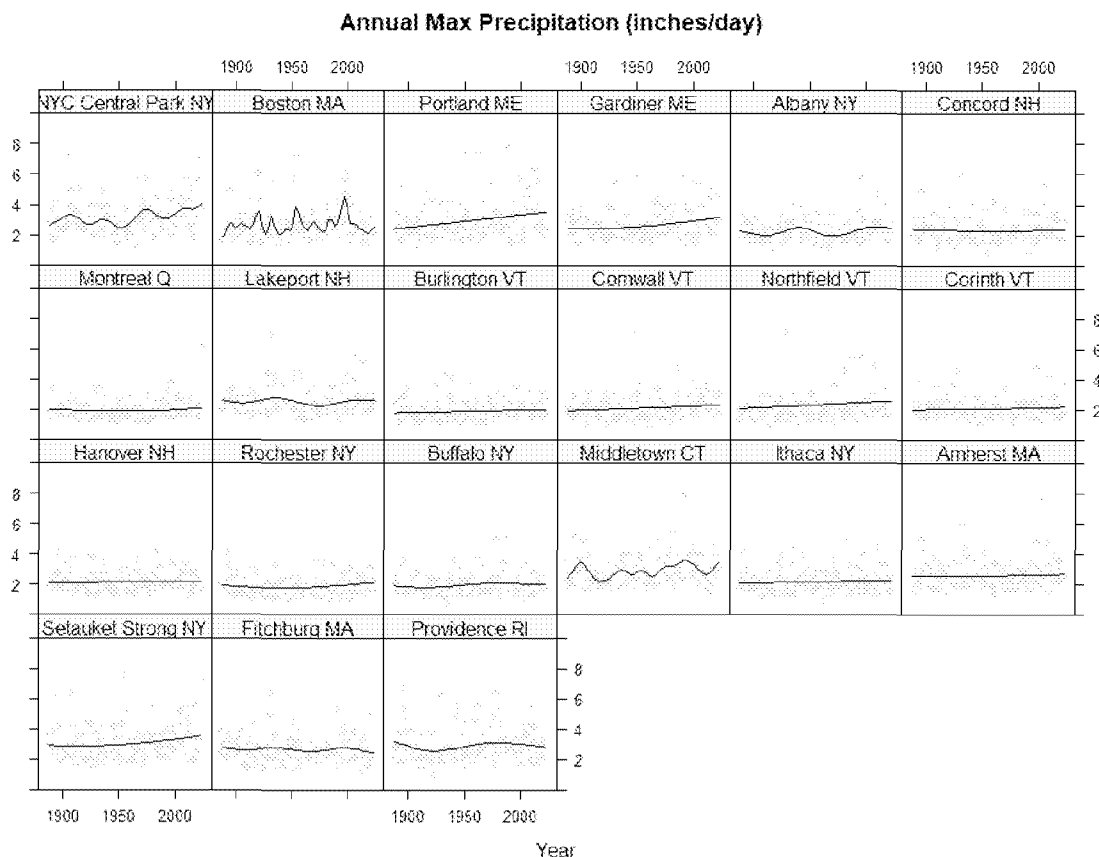


Figure 8.13 Annual maximum precipitation for 21 Northeast stations 1888 to present

Pacific Coast heavy rainfall events

The Pacific Coast receives considerable amounts of precipitation from Atmospheric River (AR) events which often last more than a day or two (e.g., Gershunov et al. 2017, Pan et al. 2024). The worst-known such event in recent history was the ArkStorm that occurred between December 1861 and January 1862, which dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 15 feet of water (Brewer 1930, Null and Hulbert 2007). Paleoclimate research has found six megastorms more severe than 1861–1862 in California during the last 1800 years, occurring at intervals of 300 years or so (Porter et al. 2011).

SIDEBAR: Perils of short data records

San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 8.1.

Event	Record (inches)	Year
3-day	6.94	2023
5-day	8.55	2023
14-day	12.62	2023

30-day	18.93	1998
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Table 8.1: Extreme rainfall records, San Francisco, 1895-2024.

The records all cluster in the more recent data. 2023 appears to be an exceptional year and since it is near the end of the sample it would point to the possibility that the climate has shifted into a potentially more hazardous state.

But if we extend the record back to 1850 the picture changes. Table 8.2 shows that the record-setting events all happened in the 1860s. Furthermore 2023 is now not even in 2nd place but falls to 3rd or 4th. Also, comparing the records of the two charts the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1998 and 2023 events, with 14- and 30-day totals about 50 percent higher.

Event	Record (inches)	Year	Rank of 130-yr extreme
3-day	8.85	1867	3
5-day	9.80	1867	3
14-day	19.05	1862	4
30-day	28.25	1862	2

Table 8.2: Extreme rainfall records, San Francisco, 1850-2024.

The characterization of the range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter et al. (2011) discovered that in the past 1,800 years at least six megastorms were more intense than the devastating 1861-62 ArkStorm struck the region. Thus, such extreme events have impacted the region about every 300 years, though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability in general and of extreme events in particular. Accurate representation of the full range of natural variability is necessary for any attribution analyses (see 6.4). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time-sample of 130 years provides an underestimation of the extreme value by up to 50% determined when adding only 45 more years of observations. Compared to millennial-scale paleoclimate evidence, an even greater underestimation would occur.

We examine occurrences of 5-day deluges as follows. In a 130-year span there are 26 5-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values. A single year may have more than one of the 26 heaviest. Each of those can be thought of as 1-in-5yr events. If there are no trends in precipitation then the total number of these events across all stations should be evenly spread out on an annual basis. In Fig. 8.14 we show the distribution in time of these events. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of these types of precipitation metrics, there is no indication of a tendency to become more frequent over time.

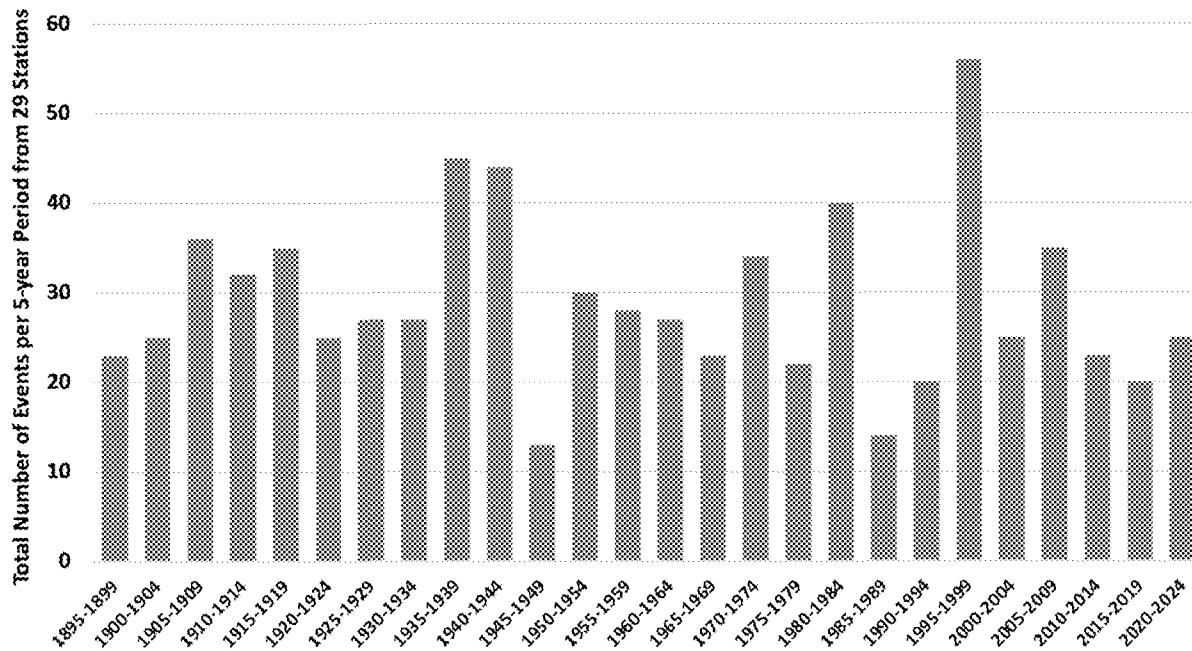


Figure 8.14. The time distribution by 5-year periods of the 26 heaviest occurrences for each station (i.e., nominal 1-in-5 year event).

Southeast heavy rainfall events

The temporal pattern of 5-day totals of the 1-in-5yr heavy events in the humid Southeast (Figure 8.15) is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA4 and NCA5 of a tendency for an increasing frequency of heavy events, due to a temporal clustering of tropical storms from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events.

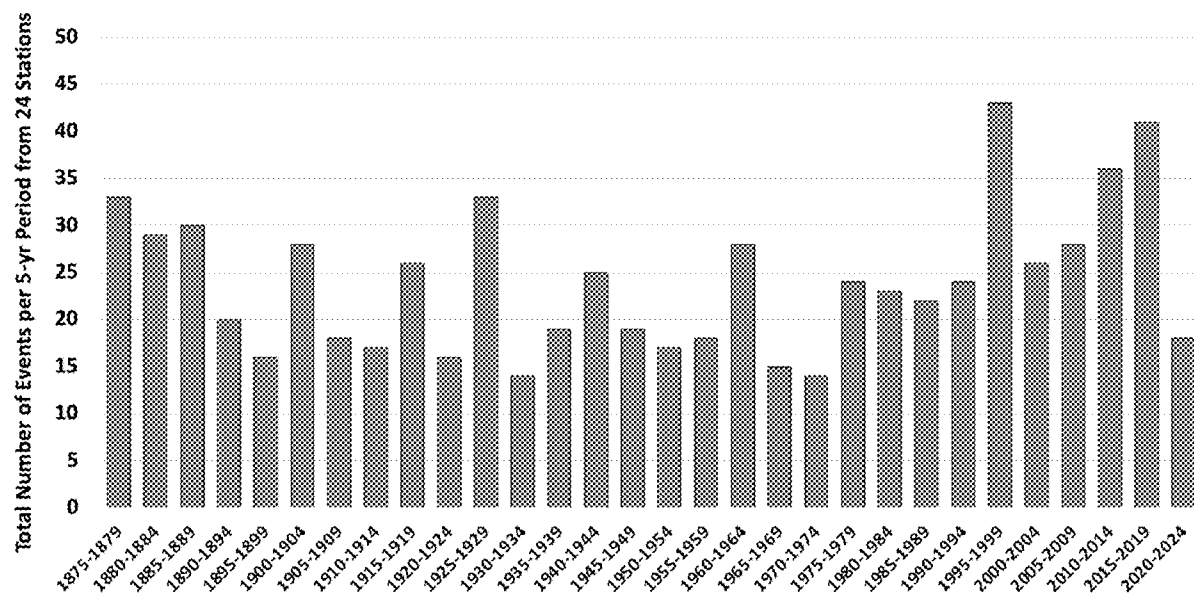


Figure 8.15. As above but for the 30 heaviest 1-in-5yr events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1875-2024.

Northwest heavy rainfall events

Fig. 8.16 shows the 27 (1-in-5yr) heaviest 3-day events for the last 135 years in 21 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest variations in time. In this region, 72% of the events occur during June to October and are dominated by tropical incursions of hurricanes, tropical storms or tropical storms that transition to extratropical systems. According to NCA4 and NCA5 this region experienced the largest increases in extreme events, so it shall be examined more closely.

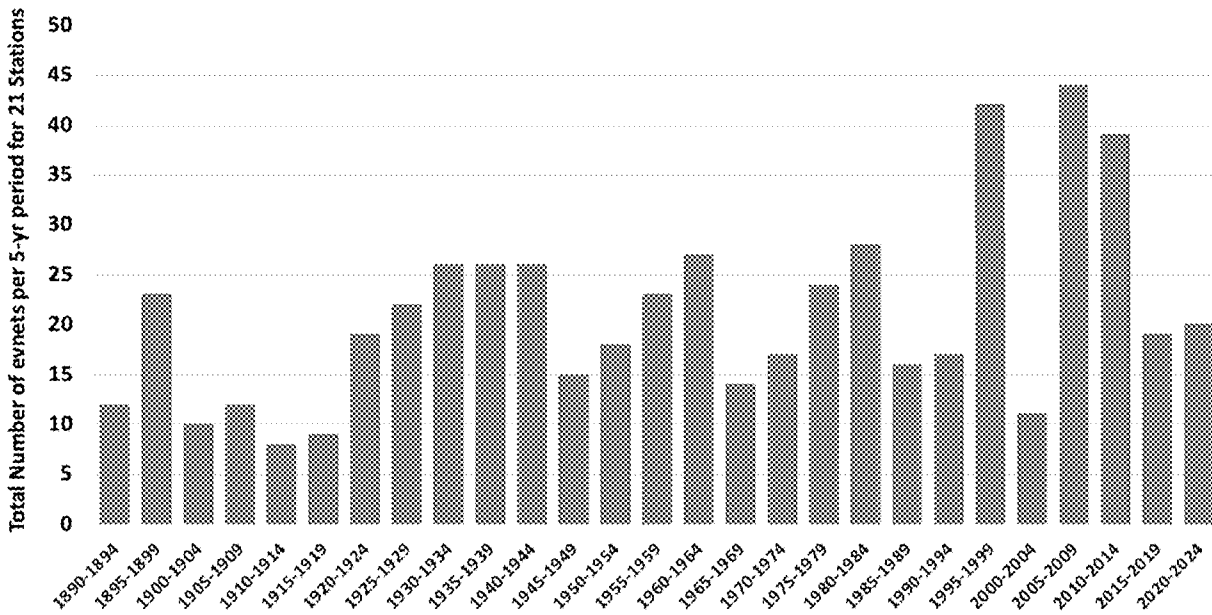


Figure 8.16. Time distribution of the heaviest 27 (1-in-5yr) heaviest 3-day precipitation events for 21 stations from NY to ME, including Montreal.

Howarth et al. (2019) report differences in the Northeast between two 18-year periods: 1979-96 and 1997-2014 (a similar region as in Fig. 8.16 that includes PA and NJ) of various precipitation extremes. One metric which indicated a dramatic increase (317%) was found for 24-hr events > 6 inches. This high increase is due to the very small numbers of such events of which there were only 6 in the first period and 25 in the second as reported for 58 stations. This high percentage increase is due to the very small numbers of the events; only 6 in the first period and 25 in the second. Most of the stations, did not record such an event suggesting these erratic, episodic events over brief, 18-yr periods, need scrutiny by additional statistical methods.

Using the information in Fig. 8.16 over the same years as Howarth et al. we find a 51% increase in the frequency of heavy events between the two periods. One can see in Fig. 8.16 that it was unfortunate that Howarth et al. ended in 2014 prior to a return to the long-term average of such events.

A feature of Howarth et al. is the use of single day totals which is questionable because extreme events are often spread across the time-of-observation boundary. Thus stations measuring at 0700 LT versus those at Midnight will have differing results for a particular event which would then have major impacts on counting these events. We use the 3-day totals in Fig. 8.16 to be sure to capture the extent of these extreme downpours. In any case, we can confirm that the period 1997 to 2014 experienced a cluster of heavier events as Howarth et al. have documented.

Howarth's most remarkable claim (317% increase in 6" days) is potentially misleading because it is a threshold statistic (see 8.3.2 above) and a ratio of small numbers over a short period. The result is not representative of *relative* extreme events for the whole region since the majority of stations never experienced a 6" total. Fig. 8.16 above determines the same number of events for each station (27 heaviest events) whose heaviest values ranged from 4.4" to 12.5" and their 27th heaviest values ranged from 3.3" to 5.0". This analysis thus allows each station to be equally represented. In other

words, if there is a region-wide increase in heavy events, it should be seen in the sum of all stations. Note too that the period of record here is 135 years vs. 36 years of Howarth et al. Except for three 5-year periods between 1995 and 2014 there is nothing statistically remarkable about the results in Fig. 8.16.

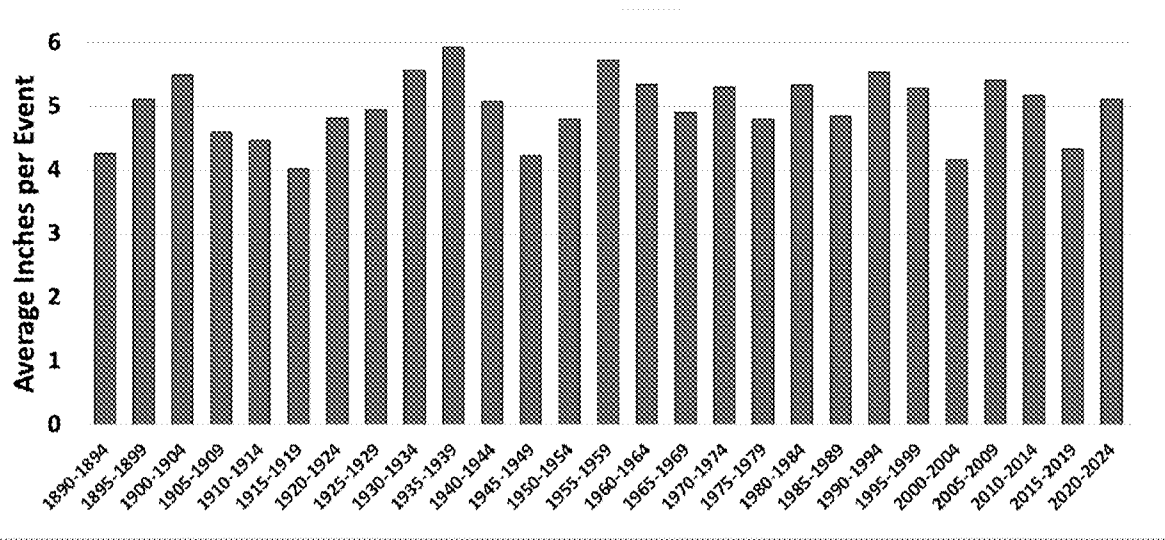


Figure 8.17. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

An interesting aspect of Northeast precipitation is that there has been no change in the amount of precipitation per heaviest event, as shown in Fig. 8.17. The trend is only $+0.02''/\text{decade}$. The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 8.15 and 8.16 suggest that though there was an uptick in the number of events during the period 1995 to 2014; the events, individually, are not becoming more intense.

Jong et al. (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded, "The autumn extreme precipitation trend over the Northeast US is primarily attributed to tropical cyclone-related events since the 1990s." The question then becomes, was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs? Jong et al. examined CMIP-6 model output which suggests that there will be fewer such systems in the 21st century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 8.17 where the amount-per-event has remained steady over the 135-year period.

For substantial urban areas there is some evidence to indicate the heaviest rainfall events may be redistributed due to the impact urban infrastructure has on the local weather (e.g., Pielke Sr. et al. 2011, Zhang et al. 2018, Yang et al. 2024). Yang et al. state, "Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with

dispersed development.” While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 8.17.

In summary, the evidence from the historical record of extreme precipitation events in the CONUS is generally not consistent from region to region so that inferences regarding trends and their projections are wrought with significant uncertainty. In most regions and perhaps all, it is our opinion that the very nature of the erratic and episodic character of extreme precipitation events renders the discovery of statistically significant changes, including a relationship to CO₂ concentrations, a result yet to be achieved (McKittrick and Christy 2019).

8.4 Summary

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Appendix: Review of IPCC and NCA Findings on Extreme Weather

The sources we review will be denoted as follows:

SREX: The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (2012)

AR5: The IPCC *Fifth Assessment Report Working Group 1* (2013).

AR6: The IPCC *Sixth Assessment Report Working Group 1* (2021).

NCA17: The *US Climate Science Special Report of the Fourth National Climate Assessment* (2017) Volume I Chapter 6.

8A.1 Overview: IPCC Assessment of signal emergence in extreme weather types (AR6 WG1 Table 12.12)

Table 8A.1 reproduces the findings of AR6 Table 12.12 which indicates, for 34 major weather event and impact types, whether a signal of anthropogenic forcing has been detected in the historical record (column 1), whether such a signal is likely to emerge by 2050 under the extreme RCP8.5 scenario (column 2) and whether it is likely to emerge by 2100 under RCP8.5 forcing (column 3). As we discuss in Ch X on attribution there are conflicting messages within the AR6 regarding attribution of extreme weather. This Table is provided here for reference.

Several patterns stand out. First, out of the 34 weather impact categories an anthropogenic signal is asserted with *high confidence* in only four, and with *medium confidence* in a further four. For the rest the IPCC does not claim to have detected anthropogenic drivers. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean) hence are not measures of extreme weather. Also two of the four *medium confidence* assertions are related to ocean chemistry and thus are likewise not related to extreme weather. The IPCC does not assert a human influence on many non-temperature weather features such as wind, precipitation, flooding, drought etc.

Second, as shown in columns 2 and 3 the IPCC expects very few such signals to emerge this century *even under the most extreme forcing scenario*. As we discuss in Section 4.2 the RCP8.5 scenario is an implausible high-end storyline, it is not a “base case” or business-as-usual projection. Yet even still most weather impacts are not expected to exhibit an anthropogenic signal this century. As will be clear from the underlying report text, natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trends reversals over time.

Climate Impact Driver Type	Climate Impact Driver Category	Already Emerged in the Historical Record?	Emerging by 2050 in Most Extreme CO2 Emissions Scenario?	Emerging by 2100 in Most Extreme CO2 Emissions Scenario?
Heat & Cold	Average air temperature	YES in most regions	YES	YES
	More heat extremes	YES in most regions	YES in land regions	YES
	Fewer cold extremes	YES in a few regions	YES in many regions	YES
	Less frost	NO	NO	NO
Wet & Dry	Average Precip. (Increase or Decrease)	NO	YES (incr) YES (decr)	YES (incr) YES (decr)
	River flooding	NO	NO	NO
	Heavy precip & pluvial flood	NO	NO	YES in a few regions
	Landslide	NO	NO	NO

	Aridity	NO	NO	NO
	Hydrologic Drought	NO	NO	NO
	Agricultural & ecological drought	NO	NO	NO
	Fire weather	NO	NO	NO
Wind	Average wind speed	NO	NO	NO
	Severe wind storm	NO	NO	NO
	Tropical cyclone	NO	NO	NO
	Sand and dust storm	NO	NO	NO
Snow and Ice	Snow, glacier & ice sheet	NO	YES in a few regions	YES Arctic snow
	Permafrost	YES	YES	YES
	Lake & river ice	NO	YES	YES
	Arctic sea ice	YES	YES	YES
	Antarctic sea ice	NO	YES	YES
	Heavy snowfall and ice storm	NO	NO	NO
	Hail	NO	NO	NO
	Snow avalanche	NO	NO	NO
Coastal	Relative sea level	NO	YES	YES
	Coastal flood	NO	NO	NO
	Coastal erosion	NO	NO	NO
Open Ocean	Average ocean temperature	YES	YES	YES
	Marine heat wave	NO	NO	NO
	Ocean acidity	NO	YES	YES
	Ocean salinity	YES	YES	YES
	Dissolved oxygen	YES (Pacific & S. Ocean)	YES	YES
Other	Air pollution weather	NO	NO	NO
	Solar or IR radiation at surface	NO	NO	NO

Table 8A.1. IPCC AR6 summary of the probable emergence of an anthropogenic signal above natural climate variability for all global or regional “climate impact drivers” (CIDs) of concern for humans and ecosystems in response to increasing atmospheric greenhouse gas concentrations (primarily CO₂). Source: Table adapted from report of Working Group I, Table 12.12). Red = high confidence; yellow = medium confidence; green = no anthropogenic signal detectable above natural variability (50% confidence).

Taking wind as an example, the IPCC claims that an anthropogenic signal has not emerged in average wind speeds, severe windstorms, tropical cyclones or sand and dust storms, nor is one expected to emerge this century even under an extreme emissions scenario. The same applies to drought and fire weather. This table alone suffices to illustrate the gap between IPCC expert assessment of extreme weather and discussions of extreme weather in the popular press. As we show below the Table reflects longstanding conclusions of the IPCC and other assessment bodies. In the next few sections we will simply present without comment excerpts from past assessment reports.

Notes: in these excerpts bold-face emphasis is added. Italicized emphasis on *confidence* terms is in the original sources. Citations contained in quoted text can be found in the underlying reports but are not reproduced here.

8A.2 Flooding

SREX (p. 176)

In the United States and Canada during the 20th century and in the early 21st century, **there is no compelling evidence for climate-driven changes in the magnitude or frequency of floods.**

AR5 (p. 214)

AR4 WGI Chapter 3 (Trenberth et al., 2007) did not assess changes in floods but AR4 WGII concluded that **there was not a general global trend in the incidence of floods** (Kundzewicz et al., 2007). SREX went further to suggest that there was low agreement and thus *low confidence* at the global scale regarding changes in the magnitude or frequency of floods or even the sign of changes.

AR5 WGII assesses floods in regional detail accounting for the fact that trends in floods are strongly influenced by changes in river management (see also Section 2.5.2). Although the most evident flood trends appear to be in northern high latitudes, where observed warming trends have been largest, in some regions no evidence of a trend in extreme flooding has been found, for example, over Russia based on daily river discharge (Shklomanov et al., 2007). Other studies for Europe (Hannaford and Marsh, 2008; Renard et al., 2008; Petrow and Merz, 2009; Stahl et al., 2010) and Asia (Jiang et al., 2008; Delgado et al., 2010) show evidence for upward, downward or no trend in the magnitude and frequency of floods, so that there is currently no clear and widespread evidence for observed changes in flooding except for the earlier spring flow in snow-dominated regions (Seneviratne et al., 2012).

In summary, **there continues to be a lack of evidence and thus *low confidence* regarding the sign of trend in the magnitude and/or frequency of floods on a global scale.**

AR6 (Ch 11 p. 1568)

The SREX (Seneviratne et al., 2012) assessed *low confidence* for observed changes in the magnitude or frequency of floods at the global scale. This assessment was confirmed by the AR5 report (Hartmann et al., 2013). The SR15 (Hoegh-Guldberg et al., 2018) found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. **While the number of studies on flood trends has increased since the AR5 report, and there were also new analyses after the release of SR15 (Berghuijs et al., 2017; Blöschl et al., 2019; Gudmundsson et al., 2019), hydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales.**

In summary, the seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). **Confidence about peak flow trends over past decades on the global scale is *low*, but there are regions experiencing increases**, including parts of Asia, southern South America, the northeast USA, northwestern Europe, and the Amazon, **and regions experiencing decreases**, including parts of the Mediterranean, Australia, Africa, and the southwestern USA.

US NCA17 pp. 240-41:

"The IPCC AR5 did not attribute changes in flooding to anthropogenic influence nor report detectable changes in flooding magnitude, duration, or frequency. Trends in extreme high values of streamflow are mixed across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude but does not provide robust evidence that these trends are attributable to human influences...

The complex mix of processes complicates the formal attribution of observed flooding trends to anthropogenic climate change and suggests that additional scientific rigor is needed in flood attribution studies. As noted above, precipitation increases have been found to strongly influence changes in flood statistics. However, in U.S. regions, **no formal attribution of precipitation changes to anthropogenic forcing has been made so far, so indirect attribution of flooding changes is not possible. Hence, no formal attribution of observed flooding changes to anthropogenic forcing has been claimed.**"

8A.3 Heatwaves

AR5 (p. 212 WG1)

Table 2.13 shows that there has been a *likely* increasing trend in the frequency of heatwaves since the middle of the 20th century in Europe and Australia and across much of Asia where there are sufficient data. However, confidence on a global scale is *medium* owing to lack of studies over Africa and South America but also in part owing to differences in trends depending on how heatwaves are defined (Perkins et al., 2012). Using monthly means as a proxy for heatwaves Coumou et al. (2013) and Hansen et al. (2012) indicate that record-breaking temperatures in recent decades substantially exceed what would be expected by chance but caution is required when making inferences between these studies and those that deal with multi-day events and/ or use more complex definitions for heatwave events. **There is also evidence in some regions that periods prior to the 1950s had more heatwaves (e.g., over the USA, the decade of the 1930s stands out and is also associated with extreme drought conditions** (Peterson et al., 2013) whereas conversely in other regions heatwave trends may have been underestimated owing to poor quality and/or consistency of data (e.g., Della-Marta et al. (2007a) over Western Europe; Kuglitsch et al. (2009, 2010) over the Mediterranean). Recent available studies also suggest that the number of cold spells has reduced significantly since the 1950s (Donat et al., 2013a, 2013c).

In summary, new analyses continue to support the AR4 and SREX conclusions that since about 1950 it is *very likely* that the numbers of cold days and nights have decreased and the numbers of warm days and nights have increased overall on the global scale, that is, for land areas with sufficient data. It is *likely* that such changes have also occurred across most of North America, Europe, Asia and Australia.

NCA17 (pp. 190-191)

Changes in warm extremes are more nuanced than changes in cold extremes. For instance, **the warmest daily temperature of the year increased in some parts of the West over the past century (Figure 6.3), but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease** (Table 6.2), most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]). The decreases in the eastern half of [the] Nation, particularly in the Great Plains, are mainly tied to the unprecedented summer heat of the 1930s Dust Bowl era, which was exacerbated by land-surface feedbacks driven by springtime precipitation deficits and land mismanagement. However, anthropogenic aerosol forcing may also have reduced summer temperatures in the Northeast and Southeast from the early 1950s to the mid-1970s, and agricultural intensification may have suppressed the hottest extremes in the Midwest.

Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). **Heat waves (6-day periods**

with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter (Figure 6.4). As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s.

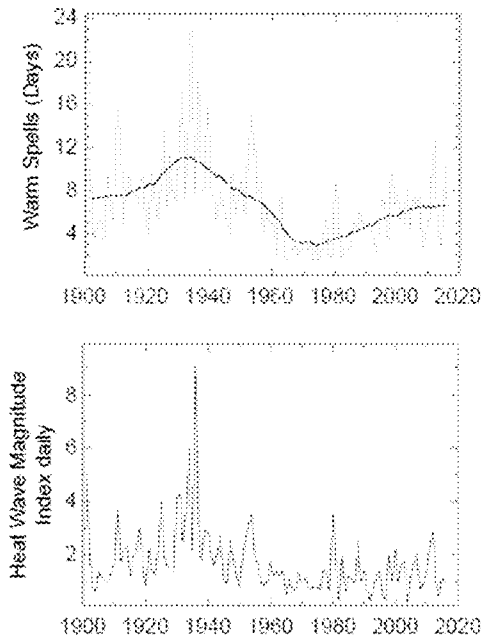


Figure 8.1: US Heat waves since 1900. Source: NCA17 Figure 6.4

AR6 (p. 1550)

In North America (Table 11.19), there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, **while there are more contrasting trends in the annual maximum daily temperatures** in parts of the USA (Figure 11.9; Lee et al., 2014; van Oldenborgh et al., 2019; Dunn et al., 2020).

8A.4 Extreme snowfall events

Note: extreme snowfall events in the US northeast are assessed in relation to winter Extratropical Cyclone (ETC) activity.

AR6 Ch 11. p. 1593

There is *high confidence* that snowfall associated with winter ETCs will decrease in the future, because increases in tropospheric temperatures lead to a lower proportion of precipitation falling as snow (O’Gorman, 2014; Rhoades et al., 2018; Zarzycki, 2018). However, there is *medium confidence* that extreme snowfall events associated with winter ETCs will change little in regions where snowfall will be supported in the future (O’Gorman, 2014; Zarzycki, 2018).

8A.5 Extreme precipitation

SREX (p. 142)

Recent studies have updated the assessment of the AR4, with more regional results now available (Table 3-2). Overall, this additional evidence confirms that **more locations and studies show an increase than a decrease in extreme precipitation, but that there are also wide regional and seasonal variations**, and trends in many regions are not statistically significant (Table 3-2)... Based on station data from Canada, the United States, and Mexico, Peterson et al. (2008a) reported that heavy precipitation has been increasing over 1950-2004, as well as the average amount of precipitation falling on days with precipitation.

AR5 (pp. 213-14)

In summary, further analyses continue to support the AR4 and SREX conclusions that **it is likely that since 1951 there have been statistically significant increases in the number of heavy precipitation events (e.g., above the 95th percentile) in more regions than there have been statistically significant decreases, but there are strong regional and subregional variations in the trends**. In particular, many regions present statistically non-significant or negative trends, and, where seasonal changes have been assessed, there are also variations between seasons (e.g., more consistent trends in winter than in summer in Europe). The overall most consistent trends towards heavier precipitation events are found in central North America (very likely increase) but assessment for Europe shows likely increases in more regions than decreases.

AR6 (p. 1560)

In North America, there is robust evidence that the magnitude and intensity of extreme precipitation has *very likely* increased since the 1950s. Both [one-day maxima] and [5-day maxima] have significantly increased in North America during 1950-2018 (Sun et al., 2020, also Figure 11.13). There is, however, regional diversity. In Canada, there is a lack of detectable trends in observed annual maximum daily (or shorter duration) precipitation (Shephard et al., 2014; Mekis et al., 2015; Vincent et al., 2018).

NCA17 pp. 213-14:

Detectability of trends (compared to internal variability) for a number of precipitation metrics over the continental United States has been examined; **however, trends identified for the U.S. regions have not been clearly attributed to anthropogenic forcing**. One study concluded that increasing precipitation trends in some north-central U.S. regions and the extreme annual anomalies there in 2013 were at least partly attributable to the combination of anthropogenic and natural forcing... **Based on current evidence, it is concluded that detectable but not attributable increases in mean precipitation have occurred over parts of the central United States**. Formal detection-attribution studies indicate a human contribution to extreme precipitation increases over the continental United States, but confidence is *low* based on those studies alone due to the short observational period, high natural variability, and model uncertainty.

In summary, based on available studies, it is concluded that for the continental United States there is *high confidence* in the detection of extreme precipitation increases, while there is *low confidence* in attributing the extreme precipitation changes purely to anthropogenic forcing.

8A.6 Tornadoes and severe convective storms

IPCC AR6 Sct. 11.7.3, p. 1594

Severe convective storms are convective systems that are associated with extreme phenomena such as tornadoes, hail, heavy precipitation (rain or snow), strong winds, and lightning.

The assessment of changes in severe convective storms in SREX (Chapter 3, Seneviratne et al., 2012) and AR5 (Chapter 12, Collins et al., 2013) is limited and focused mainly on tornadoes and hail storms. The SREX assessed that there is *low confidence* in observed trends in tornadoes and hail because of data inhomogeneities and inadequacies in monitoring systems. Subsequent literature assessed in the Climate Science Special Report (Kossin et al., 2017) led to the assessment of the observed tornado activity over the 2000s in the USA, with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days (*medium confidence*). However, there is *low confidence* in past trends for hail and severe thunderstorm winds. Climate models consistently project environmental changes that would support an increase in the frequency and intensity of severe thunderstorms that combine tornadoes, hail, and winds (*high confidence*), but there is *low confidence* in the details of the projected increase.

... In summary, because the definition of severe convective storms varies depending on the literature and the region, it is not straightforward to make a synthesizing view of observed trends in severe convective storms in different regions. In particular, observational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant, but their variability of occurrence has increased since the 1970s, particularly over the 2000s, with a decrease in the number of days per year, and an increase in the number of tornadoes on these days (*high confidence*). Detected tornadoes have also increased in Europe, but the trend depends on the density of observations.

... It is extremely difficult to detect differences in time and space of severe convective storms (Kunkel et al., 2013). Although some ingredients that are favourable for severe thunderstorms have increased over the years, others have not; thus, overall, changes in the frequency of environments favourable for severe thunderstorms have not been statistically significant... For hailstorms, such as those that caused disasters in the USA in 2018, detection of the role of climate change in changing hail storms is more difficult, because hail storms are not, in general, directly simulated by convection-permitting models and not adequately represented by the environmental parameters of coarse-resolution GCMs (Mahoney, 2020).

In summary, it is extremely difficult to detect and attribute changes in severe convective storms. There is limited evidence that extreme precipitation associated with severe convective storms has increased in some cases.

8A.7 Hurricanes and Tropical Cyclones

SREX (p. 159):

There have been no significant trends observed in global tropical cyclone frequency records, including over the present 40-year period of satellite observations (e.g., Webster et al., 2005). Regional trends in tropical cyclone frequency have been identified in the North Atlantic, but the fidelity of these trends is debated (Holland and Webster, 2007; Landsea, 2007; Mann et al., 2007a). Different methods for estimating undercounts in the earlier part of the North Atlantic tropical cyclone record provide mixed conclusions (Chang and Guo, 2007; Mann et al., 2007b; Kunkel et al., 2008; Vecchi and Knutson, 2008). Regional trends have not been detected in other oceans (Chan and Xu, 2009; Kubota and Chan, 2009; Callaghan and Power, 2011). **It thus remains uncertain whether any observed increases in tropical cyclone frequency on time scales longer than about 40 years are robust**, after accounting for past changes in observing capabilities (Knutson et al., 2010).

AR5 (pp. 216-17):

Current data sets indicate no significant observed trends in global tropical cyclone frequency over the past century and it remains uncertain whether any reported long-term increases in tropical cyclone frequency are robust, after accounting for past changes in observing capabilities (Knutson et al., 2010). **No robust trends in annual numbers of tropical storms, hurricanes and major hurricanes counts have been identified** over the past 100 years in the North Atlantic basin. Measures of land-falling tropical cyclone frequency (Figure 2.34) are generally considered to be more reliable than counts of all storms which tend to be strongly influenced by those that are weak and/or short lived. Callaghan and Power (2011) find a statistically significant decrease in Eastern Australia land-falling tropical cyclones since the late 19th century although including 2010/2011 season data this trend becomes non-significant (i.e., a trend of zero lies just inside the 90% confidence interval). Significant trends are not found in other oceans on shorter time scales (Chan and Xu, 2009; Kubota and Chan, 2009; Mohapatra et al., 2011; Weinkle et al., 2012), although Grinstead et al. (2012) find a significant positive trend in eastern USA using tide-gauge data from 1923–2008 as a proxy for storm surges associated with land-falling hurricanes. Differences between tropical cyclone studies highlight the challenges that still lie ahead in assessing long-term trends.

In summary, this assessment does not revise the SREX conclusion of *low confidence* that any reported long-term (centennial) increases in tropical cyclone activity are robust, after accounting for past changes in observing capabilities. More recent assessments indicate that **it is unlikely that annual numbers of tropical storms, hurricanes and major hurricanes counts have increased over the past 100 years in the North Atlantic basin**. Evidence, however, is for a virtually certain increase in the frequency and intensity of the strongest tropical cyclones since the 1970s in that region.

AR6 (p. 1585)

There is low confidence in most reported long-term (multidecadal to centennial) trends in TC frequency- or intensity-based metrics due to changes in the technology used to collect the best-track data. This should not be interpreted as implying that no physical (real) trends exist, but rather as indicating that either the quality or the temporal length of the data is not adequate to provide robust trend detection statements, particularly in the presence of multidecadal variability.

There are previous and ongoing efforts to homogenize the best-track data (Elsner et al., 2008; Kossin et al., 2013, 2020; Choy et al., 2015; Landsea, 2015; Emanuel et al., 2018) and there is substantial literature that finds positive trends in intensity-related metrics in the best-track

during the “satellite period”, which is generally limited to the past ~40 years (Kang and Elsner, 2012; Kishtawal et al., 2012; Kossin et al., 2013, 2020; Mei and Xie, 2016; Zhao et al., 2018; Tauvale and Tsuboki, 2019). **When best-track trends are tested using homogenized data, the intensity trends generally remain positive, but are smaller in amplitude** (Kossin et al., 2013; Holland and Bruyère, 2014). **Kossin et al. (2020) extended the homogenized TC intensity record to the period 1979–2017 and identified significant global increases in major TC exceedance probability of about 6% per decade.** In addition to trends in TC intensity, there is evidence that TC intensification rates and the frequency of rapid intensification events have increased within the satellite era (Kishtawal et al. 2012; Balaguru et al., 2018; Bhatia et al., 2018). The increase in intensification rates is found in the best-track as well as the homogenized intensity data.

A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows no trend in the frequency of U.S. landfall events (Knutson et al., 2019).

Note: The **Underlined** text referenced a study (Kossin et al. 2020) that later retracted a portion of its findings. The authors assembled a data set on global TC incidence spanning 1979 to 2017. They claimed that the global fraction of TCs reaching major status (Cat 3—5) rose from 27% in the 1979–1997 interval to 31% in the 1998–2017 interval and the difference was statistically significant. Closer examination of their results however showed a significant increase was only observed in the North Atlantic (18% to 34%) whereas in every other basin (Eastern Pacific, Western Pacific, North Indian, South Indian, South Pacific) the differences were not statistically significant. Kossin et al. issued a Correction (<https://www.pnas.org/doi/10.1073/pnas.2021573117>). The revised version said that the global probability of observing a major TC was 34% in the 1979 to 1997 interval rising to 37% in the later period and the evidence for statistical significance was now weaker, although the authors claimed that the correction did not affect their conclusions.

8A.8 Droughts

US NCA17 REPORT (Ch. 8, Wehner et al. 2017)

p. 231:

Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (very high confidence). **While by some measures drought has decreased over much of the continental United States in association with long-term increases in precipitation, neither the precipitation increases nor inferred drought decreases have been confidently attributed to anthropogenic forcing.**

The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures. (*High confidence*)

p. 233:

Drought is, of course, directly connected to seasonal precipitation totals. Figure 7.1 shows detectable observed recent changes in seasonal precipitation. In fact, the increases in

observed summer and fall precipitation are at odds with the projections in Figure 7.5. **As a consequence of this increased precipitation, drought statistics over the entire CONUS have declined.**

SREX (p. 170)

From a paleoclimate perspective recent droughts are not unprecedented, with severe ‘megadroughts’ reported in the paleoclimatic record for Europe, North America, and Australia (Jansen et al., 2007). Recent studies extend this observation to African and Indian droughts (Sinha et al., 2007; Shanahan et al., 2009): much more severe and longer droughts occurred in the past centuries with widespread ecological, political, and socioeconomic consequences. Overall, these studies confirm that in the last millennium several extreme droughts have occurred (Breda and Badeau, 2008; Kallis, 2008; Büntgen et al., 2010).

In North America, there is *medium confidence* that there has been an overall slight tendency toward less dryness (wetting trend with more soil moisture and runoff; Table 3-2), although analyses for some subregions also indicate tendencies toward increasing dryness. This assessment is based on several lines of evidence, including simulations with different hydrological models as well as PDSI and CDD estimates (Alexander et al., 2006; Andreadis and Lettenmaier, 2006; van der Schrier et al., 2006a; Kunkel et al., 2008; Sheffield and Wood, 2008a; Dai, 2011).

The most severe droughts in the 20th century have occurred in the 1930s and 1950s, where the 1930s Dust Bowl was most intense and the 1950s drought most persistent (Andreadis et al., 2005) in the United States, while in Mexico the 1950s and late 1990s were the driest periods. Recent regional trends toward more severe drought conditions were identified over southern and western Canada, Alaska, and Mexico, with subregional exceptions (Dai, 2011).

SREX (p. 172)

Overall, though new studies have furthered the understanding of the mechanisms leading to drought, there is still relatively limited evidence to provide an attribution of observed changes, in particular given the issues associated with the availability of observational data (Section 3.2.1) and the definition and computation of drought indicators (Box 3-3). This latter point was mostly identified in post-AR4 studies (Box 3-3). Moreover, regions where consistent increases in drought are identified (see ‘Observed Changes’) are only partly consistent with those where projections indicate an enhancement of drought conditions in coming decades (see next paragraphs). We thus assess that there is *medium confidence* (see also Section 3.1.5) that anthropogenic influence has contributed to some changes in the drought patterns observed in the second half of the 20th century, based on its attributed impact on precipitation and temperature changes (though temperature can only be indirectly related to drought trends; see Box 3-3). However **there is *low confidence* in the attribution of changes in droughts at the level of individual regions.**

AR5 (pp. 214-215)

Based on evidence since AR4, SREX concluded that there were not enough direct observations of dryness to suggest high confidence in observed trends globally, although there was *medium confidence* that since the 1950s some regions of the world have experienced more intense and longer droughts. The differences between AR4 and SREX are due primarily to analyses

post-AR4, differences in how both assessments considered drought and updated IPCC uncertainty guidance.

Because drought is a complex variable and can at best be incompletely represented by commonly used drought indices, discrepancies in the interpretation of changes can result. For example, Sheffield and Wood (2008) found decreasing trends in the duration, intensity and severity of drought globally. Conversely, Dai (2011a,b) found a general global increase in drought, although with substantial regional variation and individual events dominating trend signatures in some regions (e.g., the 1970s prolonged Sahel drought and the 1930s drought in the USA and Canadian Prairies). Studies subsequent to these continue to provide somewhat different conclusions on trends in global droughts and/or dryness since the middle of the 20th century (Sheffield et al., 2012; Dai, 2013; Donat et al., 2013c; van der Schrier et al., 2013).

In summary, the current assessment concludes that there is not enough evidence at present to suggest more than *low confidence* in a global-scale observed trend in drought or dryness (lack of rainfall) since the middle of the 20th century, owing to lack of direct observations, geographical inconsistencies in the trends, and dependencies of inferred trends on the index choice. Based on updated studies, AR4 conclusions regarding global increasing trends in drought since the 1970s were probably overstated. However, it is *likely* that the frequency and intensity of drought has increased in the Mediterranean and West Africa and decreased in central North America and north-west Australia since 1950.

AR6 (Drought, Observed trends, Section 11.6.2, pp. 1573-75)

p. 1573

Strong precipitation deficits have been recorded in recent decades in the Amazon (2005, 2010), south-western China (2009–2010), south-western North America (2011–2014), Australia (1997–2009), California (2014), the middle East (2012–2016), Chile (2010–2015), the Great Horn of Africa (2011), among others (van Dijk et al., 2013; Mann and Gleick, 2015; Rowell et al., 2015; Marengo and Espinoza, 2016; Dai and Zhao, 2017; Garreaud et al., 2017, 2020; Marengo et al., 2017; Brito et al., 2018; Cook et al., 2018). **Global studies generally show no significant trends in SPI time series** (Orlowsky and Seneviratne, 2013; Spinoni et al., 2014), **and in derived drought frequency and severity data** (Spinoni et al., 2019), with very few regional exceptions (Section 11.9 and Figure 11.17).

p. 1574

For AR6 regions, several studies suggest an increase in the frequency and areal extent of soil moisture deficits, with examples in East Asia (Cheng et al., 2015; Y. Qin et al., 2015; Jia et al., 2018), Western and Central Europe (Trnka et al., 2015b), and the Mediterranean (Hanel et al., 2018; Moravec et al., 2019; Markonis et al., 2021). **Nonetheless, some analyses also show no long-term trends in soil drying in some AR6 regions – for example, in Eastern North America (Park Williams et al., 2017) and Central North America** (Seager et al., 2019), as well as in North Eastern Africa (Kew et al., 2021).

There is evidence based on streamflow records of increased hydrological droughts in East Asia (D. Zhang et al., 2018) and southern Africa (Gudmundsson et al., 2019). **In areas of Western and Central Europe and Northern Europe, there is no evidence of changes in the severity of hydrological droughts since 1950** based on flow reconstructions (Caillouet et al., 2017; Barker et al., 2019) and observations (Vicente-Serrano et al., 2019). **In North**

America, depending on the methods, datasets and study periods, there are differences between studies that suggest an increase (Shukla et al., 2015; Udall and Overpeck, 2017) versus a decrease in hydrological drought frequency (Mo and Lettenmaier, 2018), but in general there is strong spatial variability (Poshtiri and Pal, 2016). Streamflow observation reference networks of near-natural catchments have also been used to isolate the effect of climate trends on hydrological drought trends in a few regions, but these show limited trends in Northern Europe and Western and Central Europe (Stahl et al., 2010; Bard et al., 2015; Harrigan et al., 2018), North America (Dudley et al., 2020) and most of Australia, with the exception of Eastern and Southern Australia (X.S. Zhang et al., 2016).

p. 1575

Few AR6 regions show observed increases in meteorological drought (Section 11.9), mostly in Africa and South America (NES: *high confidence*; WAF, CAF, ESAF, SAM, SWS, SSA, SAS: *medium confidence*); a few others show a decrease (WSB, ESB, NAU, CAU, NEU, CNA: *medium confidence*). There are stronger signals indicating observed increases in agricultural and ecological drought (Section 11.9), which highlights the role of increased [evapotranspiration], driven by increased [Atmospheric Evaporative Demand], for these trends (Sections 11.6.2.3, 11.6.2.5). Past increases in agricultural and ecological droughts are found on all continents and several regions (WAF, CAF, WSAF, ESAF, WCA, ECA, EAS, SAU, MED, WCE, NES: *medium confidence*), while decreases are found only in one AR6 region (NAU: *medium confidence*). The more limited availability of datasets makes it more difficult to assess historical trends in hydrological drought at regional scale (Section 11.9). Increasing (MED: *high confidence*; WAF, EAS, SAU: *medium confidence*) and decreasing (NEU, SES: *medium confidence*) trends in hydrological droughts have only been observed in a few regions.

AR6 on Attribution (p. 1577)

There are only two AR6 regions in which there is at least *medium confidence* that human-induced climate change has contributed to changes in meteorological droughts (Section 11.9). In South-western South America (SSW), there is *medium confidence* that human-induced climate change has contributed to an increase in meteorological droughts (Boisier et al., 2016; Garreaud et al., 2020), while in Northern Europe (NEU), there is *medium confidence* that it has contributed to a decrease in meteorological droughts (Gudmundsson and Seneviratne, 2016) (Section 11.9). **In other AR6 regions, there is inconclusive evidence in the attribution of long-term trends, but a human contribution to single meteorological events or subregional trends has been identified in some instances... In North America, the human influence on precipitation deficits is complex (Wehner et al., 2017), with low confidence in the attribution of long-term changes in meteorological drought in AR6 regions.**

On May 6, 2025, at 5:25 PM, John Christy <climateman60@gmail.com> wrote:

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To: John Christy <climateman60@gmail.com>

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From: Ross McKittrick <ross.mckittrick@gmail.com>
Sent: Tuesday, May 6, 2025 10:20 PM
To: Steven Koonin
Cc: John Christy; Judith Curry; Roy W. Spencer; Travis Fisher
Subject: Re: Ch 8 Extreme weather

Thanks John and we'll take it from here for a few days. You and Sherry enjoy Hawaii.

On Tue, May 6, 2025 at 10:02 PM Steven Koonin <steven.koonin@gmail.com> wrote:

I was expecting to read/comment/edit Chapter 8 tomorrow (Wednesday), so I'll use this version. Roy, if you beat me to a summary, that's fine, else I'll take it on.

John, do decouple for at least a few days. I've made the mistake of not doing so on a few vacations, with great regrets afterward.

Steven Koonin

On May 6, 2025, at 21:53, John Christy <climateman60@gmail.com> wrote:

All

Here is a cleaned up version of chapter 8 which you will likely not see until 7 May, so that is the date.

My preference is for someone to read the thing and write the summary (8.4) based upon what a fresh set of eyes would conclude. Steve? Roy?

Ross. The panel charts of the individual station precipitation take up a lot of real estate and I think the value per acre is low. Since you calculated 3 statistics for each station, could you craft a bar chart or something to show that result? You would then have 9 charts, one for each of the 3 statistics and one each of the three regions. The nine charts may be panelized and fit on one plot. I know for us it's important for people to see the actual data (which is why I had those colored bar charts - now monochromatic), but it may be overkill for this document.

As to one of the statistics, I believe 3-day totals will be more meaningful and accurate than 1-day totals. I could send you a file of the heaviest 3-day total for each station and each year and you can do the analysis from there.

I especially like the way you parsed the Sidebar and I hope smart people will finally understand that when dealing with climate, our sample is pathetically small from which to draw hard conclusions.

I also enjoyed the added words on LTP. In fact do you have a few sentences that expand that a little to talk about the erratic nature of precipitation (spatial and temporal) in fancy statistical terms which means finding statistical significance in such a variable is a tough job?

I redid the number-of-event bar charts - all one color now.

I reran the Heatwave results to use 6-day periods as did NCA5. NCA5 was slick though. By choosing 1961-90 their background climatology was cold relative to decades before and since, so that results outside of those 30 years would produce a lot of days that exceed the percentile threshold. Then in the urban heatwave website, they started in 1960, assuring a result that more temps would exceed the threshold in post-1990 years.

That's all I've got.

Aloha

John C.

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Director, Earth System Science Center
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<8 Extreme weather.JRC.May07.docx>

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Sent: Thursday, May 8, 2025 1:45 PM
To: Judith Curry; John Christy
Cc: Steven Koonin; Ross McKittrick; Travis Fisher
Subject: Re: Ch 8 Extreme weather

This way forward is fine with me.
-Roy

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I think starting with IPCC up front is very useful to provide a reference point, and discussing problems with NCA motivates the unpublished data analysis

On Thu, May 8, 2025 at 10:36 AM John Christy <climateman60@gmail.com> wrote:
Ultimately the order will likely not matter. We are somewhat conflicted. On one hand we show the Assessments are consistent with our conclusions about extreme weather, but on the other hand we find them (especially NCAs) deceptive in presenting the information that skews their results to lean toward alarmism. This is true of other chapters as well.

At the least we should mention this nuance perhaps up front.

John C.

Sent from my iPhone

On May 8, 2025, at 6:23 AM, Judith Curry <curry.judith@gmail.com> wrote:

I also agree with this organization, was thinking the same thing

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Attached are my comments/edits on Chapter 8.

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SEK

PS Note for interest and amusement the AI-generated summary section.

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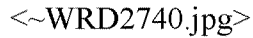
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On Mon, May 5, 2025 at 7:47 PM Ross McKittrick
<ross.mckittrick@gmail.com> wrote:

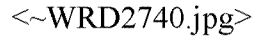
I have wrangled the extreme weather chapter into something I hope flows better and is more readable. I adopted Judy's editorial changes and then the new changes I made are in red. I added some new Figures showing results on PC and SE data and will add the NE chart when I get the data. I also made some labeling suggestions including for the 3 rainfall charts that are hard to understand. Section summaries and an overall summary are still needed.

Ross

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From: Ross McKittrick [ross.mckittrick@gmail.com]
Sent: 5/9/2025 6:45:24 PM
To: Roy Spencer [roywspencer@hotmail.com]
CC: Judith Curry [curry.judith@gmail.com]; John Christy [climatemanager60@gmail.com]; Steven Koonin [steven.koonin@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]
Subject: Re: Ch 8 Extreme weather
Attachments: 8 Extreme weather.May09[RM].docx

In the attached Extreme Weather chapter draft I moved the IPCC/NCA excerpts back into the main body per the discussion here and renumbered all the sections and figures mutatis mutandis.

The AI summary is not bad but does need some work. Admittedly it's a lot of stuff to summarize, although the recurring theme is that trends aren't detectable and attribution to GHGs is currently not possible, in general.

On Thu, May 8, 2025 at 1:45 PM Roy Spencer <roywspencer@hotmail.com> wrote:

This way forward is fine with me.

-Roy

From: Judith Curry <curry.judith@gmail.com>

Sent: Thursday, May 8, 2025 12:43 PM

To: John Christy <climatemanager60@gmail.com>

Cc: Steven Koonin <steven.koonin@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>

Subject: Re: Ch 8 Extreme weather

I think starting with IPCC up front is very useful to provide a reference point, and discussing problems with NCA motivates the unpublished data analysis

On Thu, May 8, 2025 at 10:36 AM John Christy <climatemanager60@gmail.com> wrote:

Ultimately the order will likely not matter. We are somewhat conflicted. On one hand we show the Assessments are consistent with our conclusions about extreme weather, but on the other hand we find them (especially NCAs) deceptive in presenting the information that skews their results to lean toward alarmism. This is true of other chapters as well.

At the least we should mention this nuance perhaps up front.

John C.

Sent from my iPhone

On May 8, 2025, at 6:23 AM, Judith Curry <curry.judith@gmail.com> wrote:

I also agree with this organization, was thinking the same thing

On Thu, May 8, 2025 at 8:52 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Attached are my comments/edits on Chapter 8.

I'd like to make a strong pitch to reorder the text so that the survey of previous assessments comes first, then followed by the new work from John and Ross. There are several reasons for this that I can elaborate, but the most important is that the official assessments already make the case and, no offense guys, carry far more authority in the non-expert world.

SEK

PS Note for interest and amusement the AI-generated summary section.

From: Ross McKittrick <ross.mckittrick@gmail.com>

Sent: Tuesday, May 6, 2025 1:05 PM

To: John Christy <climateman60@gmail.com>

Cc: Judith Curry <curry.judith@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Steven Koonin <steven.koonin@googlemail.com>

Subject: Re: Ch 8 Extreme weather

Here's another edition of Ch 8 on extremes taking Judy's and John's points into account. The IPCC/NCA review is ported to an Appendix. I added a paragraph about LTP to the intro. I've incorporated the NE data. The bulk of the chapter is John's US temperature and precip data analysis with some additional material on wildfires, drought and TCs. For the US temperature extremes I moved the range figure to come just after the hot/cold extremes count because I think they both make a coherent point namely that the US becoming less extreme because heat events are rising more slowly than cold events are warming. There will still need to be an overall chapter summary but I'm going to move on to other chapters now. I'll put this in the Dropbox.

On Tue, May 6, 2025 at 12:12 PM John Christy <climateman60@gmail.com> wrote:

All

We can fill in without much trouble the change, or lack thereof, of "high impact" weather events (mainly wind and flooding like hurricanes, tornadoes etc) in the CONUS Extreme chapter. The temp and precip metrics are important because they are just long enough to essentially tell us Mother Nature has a mind of her own.

1. I'll look at Ross's version of 8 soon, but my hope was that Ross would translate the statistical remarks into the correct language(eg are their more precise words that chaotic, episodic, stochastic, etc).
2. We have analyses of the CONUS with more complete datasets than the NCA used (recall NCA analyses depended essentially on a small group at NCEI using datasets that (a) were not very consistent in time, (b) could promote alarm and (c) already easy for them to get to. Our datasets have literally hundreds of thousands of manually keyed-in observations for temporal consistency. In other words, this lets people know we can address these issues from soup to nuts - we're not armchair climate scientists ... we can reproduce what they did, but make the analysis more comprehensive to address the questions.

John C.

Sent from my iPhone

On May 6, 2025, at 4:14 AM, Ross McKittrick

<ross.mckittrick@gmail.com> wrote:

Just read your attribution chapter. I hadn't picked up on the gap between IPCC Ch 11 vs Ch 12 language but i see your point that rather than promoting one set of attribution findings we should explain that even within the same AR different authors assessed things differently. One option is to leave Ch 6 where it is but reverse the order of Ch 7 and 8 while retitling the latter as you suggest. That way, having established the extreme weather types for which there are no detectable trends it will more naturally follow that they won't be discussed in the attribution chapter.

On Tue, May 6, 2025 at 9:45 AM Judith Curry <curry.judith@gmail.com> wrote:

Ok, but the summary table (12.12 from AR6) is inconsistent with conclusions in AR6 ch 11 (I point this out in section 6.4 of my attribution chapter).

In my mind, the main point is disagreement and ambiguity I would suggest chapter 8 going before chapter 6, retitling it as US Weather and Climate Extremes, and make it more of a data chapter, not an attribution chapter (I would put table 12.12 in the attribution chapter if you want to include the actual table)

On Tue, May 6, 2025 at 6:39 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

I like john's material too which is why I included it and am working on the extended regional analyses. But on this topic people are heavily primed to believe that extreme weather of all kinds is getting worse due to climate change. The assertion shows up everywhere climate change is discussed including in academic papers. I think it is very valuable to show people that neither the IPCC nor the NCA support such this view. We should at least lead off with the summary table. The library of quotes can go to an appendix but I have found in my public speaking that they have considerable persuasive force for most people. We also need to address floods, droughts, hurricane landfalls, tornadoes etc. I don't see any reason to delete all that material.

On Tue, May 6, 2025 at 9:22 AM Judith Curry <curry.judith@gmail.com> wrote:

I actually liked John's chapter. I would have retitled it "US temperature and rainfall extremes"

I think this is more relevant than a complete rehash of everything the last 3 IPCC reports have stated for every conceivable severe weather event.

John's version meshes very well with my version of chapter 6. Read especially section 6.4 of my chapter. I note a discrepancy between chapters 11 and 12 in terms of detecting and attributing extreme events. This is the main point in my opinion, there is ambiguity in all this. Lets focus on pointing out the problems/challenges, and topics that are particularly relevant for the US

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Ross

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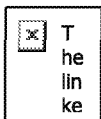
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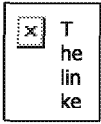
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8 Extreme weather in the US and elsewhere

8.1 Introduction

Weather extremes, usually related to temperature and/or precipitation, can disrupt infrastructure and therefore endanger human health and wellbeing. The issue is not whether extremes occur, for they are intrinsic to the chaotic climate system. Rather, it is whether there are long-term (decadal scale) changes in the frequency or character of extremes (“detection”), as well as the extent to which such changes and the attendant changes in hazards are caused by anthropogenic emissions of greenhouse gases (“attribution”; e.g., IPCC AR6 Seneviratne et al. 2021).

It is naïve to assume that any recent unprecedented extreme event is caused by human influences on the climate. That assumption is wrong in two ways. First, climate is about the statistical properties of weather over decades, not single events. And second, there are only about 130 years of reliable observational records that can be analyzed statistically. That brief interval does not begin to contain all of the extreme events that the climate system can create on its own. Over geologic time the climate system has generated an (essentially) infinite variety of weather patterns and extremes that humans have never observed, and thus are absent from the databases used to determine extreme statistics.¹ [see *Perils of short data records* below]. For that reason, attributing an extreme event unprecedented in the record requires assumptions about the magnitude of natural variations.

This is especially true for precipitation events. The hydrological literature has long noted the phenomenon of *Long Term Persistence* (LTP) in rainfall data (Hurst 1951, Cohn and Lins 2005, Markonis and Koutsoyiannis 2015). LTP has a formal mathematical definition but it can be thought of intuitively as the presence of natural variations with strong autocorrelation properties that result in cycle-like behavior on long time scales. The presence of LTP requires long records to accurately estimate variability. Analysis of records short relative to the LTP scale will tend to underestimate variability, therefore overstating the significance of apparent trends and underestimating the likelihood of extreme events (Cohn and Lins 2005).

A good example of LTP is the eight-century long record of the annual minimum height of the Nile River observed at Roda Island in Cairo shown below in Figure 8.1.1. Since human influences on the global climate were negligible before the 20th century, the century-scale variability of the thirty-year average is entirely natural; Egyptians of the seventh and eight centuries would have been incorrect to assume that the worsening drought during that time was the “new normal.”

¹ For example, under the simplest statistical assumptions there is a 37 percent chance that a 100-year event is NOT present in a century-long record.

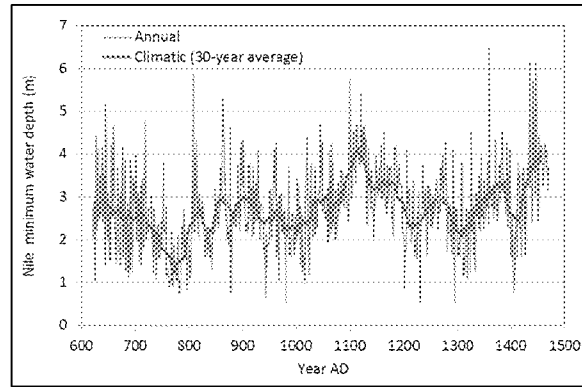


Figure 8.1.1: Nile River discharge [details, source]

With these caveats in mind we examine the evidence for changes in selected weather and climate extremes. It has become routine in media discussions, government and private sector discussions and even in some academic literature to make generalized assertions that extreme weather of all types is getting worse due to GHGs and climate change. Yet expert assessments have not typically drawn such sweeping conclusions and instead have emphasized the difficulty both of identifying specific trends and establishing a causal connection with anthropogenic forcing. For the benefit of readers who may not have read the relevant reports we will begin with extended excerpts of findings from previous IPCC and NCA assessments, then in the remainder of this chapter survey additional data relevant to US and global extreme weather trends.

8.2 Review of IPCC and NCA Findings on Extreme Weather

The sources we review will be denoted as follows:

SREX: The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (2012)

AR5: The IPCC *Fifth Assessment Report Working Group 1* (2013).

AR6: The IPCC *Sixth Assessment Report Working Group 1* (2021).

NCA17: The *US Climate Science Special Report of the Fourth National Climate Assessment* (2017) Volume I Chapter 6.

8.2.1 Overview: IPCC Assessment of signal emergence in extreme weather types (AR6 WG1 Table 12.12)

Table 8.2.1 reproduces the findings of AR6 Table 12.12 which indicates, for 34 major weather event and impact types, whether a signal of anthropogenic forcing has been detected in the historical record (column 1), whether such a signal is likely to emerge by 2050 under the extreme RCP8.5 scenario (column 2) and whether it is likely to emerge by 2100 under RCP8.5 forcing (column 3). It should be borne in mind that the latter two columns suffer from the deficiencies of GCMs discussed in Chapter XX. And as we discussed in Ch X on attribution, AR6 offers conflicting messages about attribution of extreme weather. Nevertheless, we provide this Table for reference.

Several patterns stand out. First, detection of an anthropogenic signal is asserted with *high confidence* in only four of the 34 weather impact categories, and with *medium confidence* in a

further four. The IPCC does NOT claim to have detected an anthropogenic signal in the remaining 26 categories. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean), which are not measures of extreme weather. Further, two of the four *medium confidence* assertions are related to ocean chemistry and also not related to extreme weather. The IPCC does NOT assert a detectable human influence on many non-temperature weather features such as wind, precipitation, flooding, and drought.

Second, columns 2 and 3 show that the IPCC expects very few anthropogenic trends to emerge within this century, *even under the most extreme forcing scenario*. As we discuss in Section 4.2 the RCP8.5 scenario is an implausible high-end storyline, not a “base case” or “business-as-usual” projection. Even so, most weather impacts are not expected to show an anthropogenic signal this century. Natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trend reversals over time.

Climate Impact Driver Type	Climate Impact Driver Category	Already Emerged in the Historical Record?	Emerging by 2050 in Most Extreme CO2 Emissions Scenario?	Emerging by 2100 in Most Extreme CO2 Emissions Scenario?
Heat & Cold	Average air temperature	YES in most regions	YES	YES
	More heat extremes	YES in most regions	YES in land regions	YES
	Fewer cold extremes	YES in a few regions	YES in many regions	YES
	Less frost	NO	NO	NO
Wet & Dry	Average Precip. (Increase or Decrease)	NO	YES (incr) YES (decr)	YES (incr) YES (decr)
	River flooding	NO	NO	NO
	Heavy precip & pluvial flood	NO	NO	YES in a few regions
	Landslide	NO	NO	NO
	Aridity	NO	NO	NO
	Hydrologic Drought	NO	NO	NO
	Agricultural & ecological drought	NO	NO	NO
	Fire weather	NO	NO	NO
Wind	Average wind speed	NO	NO	NO
	Severe wind storm	NO	NO	NO
	Tropical cyclone	NO	NO	NO
	Sand and dust storm	NO	NO	NO
Snow and Ice	Snow, glacier & ice sheet	NO	YES in a few regions	YES Arctic snow
	Permafrost	YES	YES	YES
	Lake & river ice	NO	YES	YES
	Arctic sea ice	YES	YES	YES
	Antarctic sea ice	NO	YES	YES
	Heavy snowfall and ice storm	NO	NO	NO
	Hail	NO	NO	NO
	Snow avalanche	NO	NO	NO
Coastal	Relative sea level	NO	YES	YES
	Coastal flood	NO	NO	NO
	Coastal erosion	NO	NO	NO
Open Ocean	Average ocean temperature	YES	YES	YES
	Marine heat wave	NO	NO	NO
	Ocean acidity	NO	YES	YES
	Ocean salinity	YES	YES	YES
	Dissolved oxygen	YES (Pacific & S. Ocean)	YES	YES
Other	Air pollution weather	NO	NO	NO
	Solar or IR radiation at surface	NO	NO	NO

Table 8.2.1. IPCC AR6 summary of the probable emergence of an anthropogenic signal above natural climate variability for all global or regional “climate impact drivers” (CIDs) of concern for humans and ecosystems in response to increasing atmospheric greenhouse gas concentrations (primarily CO₂). Source: Table adapted from report of Working Group I, Table 12.12). Red = high confidence; yellow = medium confidence; green = no anthropogenic signal detectable above natural variability (50% confidence).

Taking wind as an example, the IPCC claims that an anthropogenic signal has NOT emerged in average wind speeds, severe windstorms, tropical cyclones, or sand and dust storms, and none are expected to emerge this century even under an extreme emissions scenario. The same applies to drought and fire weather. This table alone suffices to illustrate the gap between IPCC expert assessments of extreme weather and discussions in the popular media and political arenas. As we show below the Table reflects longstanding conclusions of the IPCC and other assessment bodies. In the next few sections we will simply present without comment excerpts from past assessment reports.² In selecting these excerpts, we’ve focused on the highest-level summaries to avoid accusations of bias through “cherry picking”.

² In these excerpts we have added **bold-face** emphasis, while *italicized* emphasis on confidence terms appears in the original sources. Citations in quoted text can be found in the underlying reports but are not reproduced here.

8.2.2 Flooding

SREX (p. 176)

In the United States and Canada during the 20th century and in the early 21st century, **there is no compelling evidence for climate-driven changes in the magnitude or frequency of floods.**

AR5 (p. 214)

AR4 WGI Chapter 3 (Trenberth et al., 2007) did not assess changes in floods but AR4 WGII concluded that **there was not a general global trend in the incidence of floods** (Kundzewicz et al., 2007). SREX went further to suggest that there was low agreement and thus *low confidence* at the global scale regarding changes in the magnitude or frequency of floods or even the sign of changes.

AR5 WGII assesses floods in regional detail accounting for the fact that trends in floods are strongly influenced by changes in river management (see also Section 2.5.2). Although the most evident flood trends appear to be in northern high latitudes, where observed warming trends have been largest, in some regions no evidence of a trend in extreme flooding has been found, for example, over Russia based on daily river discharge (Shklomanov et al., 2007). Other studies for Europe (Hannaford and Marsh, 2008; Renard et al., 2008; Petrow and Merz, 2009; Stahl et al., 2010) and Asia (Jiang et al., 2008; Delgado et al., 2010) show evidence for upward, downward or no trend in the magnitude and frequency of floods, so that there is currently no clear and widespread evidence for observed changes in flooding except for the earlier spring flow in snow-dominated regions (Seneviratne et al., 2012).

In summary, **there continues to be a lack of evidence and thus *low confidence* regarding the sign of trend in the magnitude and/or frequency of floods on a global scale.**

AR6 (Ch 11 p. 1568)

The SREX (Seneviratne et al., 2012) assessed *low confidence* for observed changes in the magnitude or frequency of floods at the global scale. This assessment was confirmed by the AR5 report (Hartmann et al., 2013). The SR15 (Hoegh-Guldberg et al., 2018) found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. **While the number of studies on flood trends has increased since the AR5 report, and there were also new analyses after the release of SR15 (Berghuijs et al., 2017; Blöschl et al., 2019; Gudmundsson et al., 2019), hydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales.**

In summary, the seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). **Confidence about peak flow trends over past decades on the global scale is low, but there are regions experiencing increases**, including parts of Asia, southern South America, the northeast USA, northwestern Europe, and the Amazon, **and regions experiencing decreases**, including parts of the Mediterranean, Australia, Africa, and the southwestern USA.

US NCA17 pp. 240-41:

"The IPCC AR5 did not attribute changes in flooding to anthropogenic influence nor report detectable changes in flooding magnitude, duration, or frequency. Trends in extreme high values of streamflow are mixed across the United States. Analysis of 200 U.S. stream gauges

indicates areas of both increasing and decreasing flooding magnitude but does not provide robust evidence that these trends are attributable to human influences...

The complex mix of processes complicates the formal attribution of observed flooding trends to anthropogenic climate change and suggests that additional scientific rigor is needed in flood attribution studies. As noted above, precipitation increases have been found to strongly influence changes in flood statistics. However, in U.S. regions, **no formal attribution of precipitation changes to anthropogenic forcing has been made so far, so indirect attribution of flooding changes is not possible. Hence, no formal attribution of observed flooding changes to anthropogenic forcing has been claimed.**"

8.2.3 Heatwaves

AR5 (p. 212 WG1)

Table 2.13 shows that there has been a *likely* increasing trend in the frequency of heatwaves since the middle of the 20th century in Europe and Australia and across much of Asia where there are sufficient data. However, confidence on a global scale is *medium* owing to lack of studies over Africa and South America but also in part owing to differences in trends depending on how heatwaves are defined (Perkins et al., 2012). Using monthly means as a proxy for heatwaves Coumou et al. (2013) and Hansen et al. (2012) indicate that record-breaking temperatures in recent decades substantially exceed what would be expected by chance but caution is required when making inferences between these studies and those that deal with multi-day events and/ or use more complex definitions for heatwave events. **There is also evidence in some regions that periods prior to the 1950s had more heatwaves (e.g., over the USA, the decade of the 1930s stands out and is also associated with extreme drought conditions** (Peterson et al., 2013) whereas conversely in other regions heatwave trends may have been underestimated owing to poor quality and/or consistency of data (e.g., Della-Marta et al. (2007a) over Western Europe; Kuglitsch et al. (2009, 2010) over the Mediterranean). Recent available studies also suggest that the number of cold spells has reduced significantly since the 1950s (Donat et al., 2013a, 2013c).

In summary, new analyses continue to support the AR4 and SREX conclusions that since about 1950 it is *very likely* that the numbers of cold days and nights have decreased and the numbers of warm days and nights have increased overall on the global scale, that is, for land areas with sufficient data. It is *likely* that such changes have also occurred across most of North America, Europe, Asia and Australia.

NCA17 (pp. 190-191)

Changes in warm extremes are more nuanced than changes in cold extremes. For instance, **the warmest daily temperature of the year increased in some parts of the West over the past century (Figure 6.3), but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease** (Table 6.2), most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]). The decreases in the eastern half of [the] Nation, particularly in the Great Plains, are mainly tied to the unprecedented summer heat of the 1930s Dust Bowl era, which was exacerbated by land-surface feedbacks driven by springtime precipitation deficits and land mismanagement. However, anthropogenic aerosol forcing may also have reduced summer temperatures in the Northeast and Southeast from the early 1950s to the mid-1970s, and agricultural intensification may have suppressed the hottest extremes in the Midwest.

Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). **Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter (Figure 6.4).** As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s.

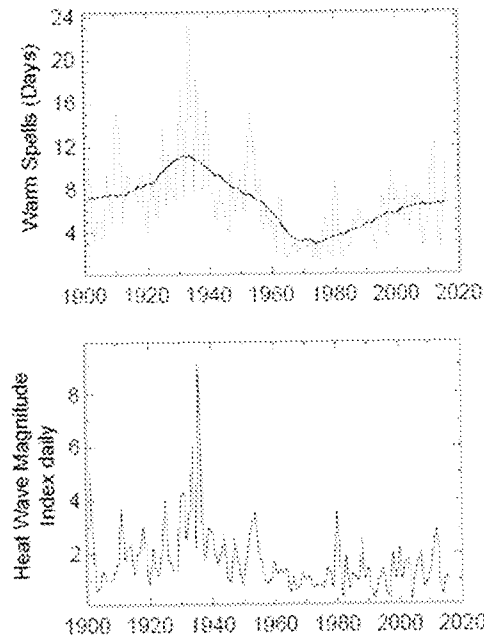


Figure 8.2.1: US Heat waves since 1900. Source: NCA17 Figure 6.4

AR6 (p. 1550)

In North America (Table 11.19), there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, **while there are more contrasting trends in the annual maximum daily temperatures** in parts of the USA (Figure 11.9; Lee et al., 2014; van Oldenborgh et al., 2019; Dunn et al., 2020).

8.2.4 Extreme snowfall events

Note: extreme snowfall events in the US northeast are assessed in relation to winter Extratropical Cyclone (ETC) activity.

AR6 Ch 11. p. 1593

There is *high confidence* that snowfall associated with winter ETCs will decrease in the future, because increases in tropospheric temperatures lead to a lower proportion of precipitation falling as snow (O’Gorman, 2014; Rhoades et al., 2018; Zarzycki, 2018). However, there is

medium confidence that extreme snowfall events associated with winter ETCs will change little in regions where snowfall will be supported in the future (O’Gorman, 2014; Zarzycki, 2018).

8.2.5 Extreme precipitation

SREX (p. 142)

Recent studies have updated the assessment of the AR4, with more regional results now available (Table 3-2). Overall, this additional evidence confirms that **more locations and studies show an increase than a decrease in extreme precipitation, but that there are also wide regional and seasonal variations**, and trends in many regions are not statistically significant (Table 3-2)... Based on station data from Canada, the United States, and Mexico, Peterson et al. (2008a) reported that heavy precipitation has been increasing over 1950-2004, as well as the average amount of precipitation falling on days with precipitation.

AR5 (pp. 213-14)

In summary, further analyses continue to support the AR4 and SREX conclusions that **it is likely that since 1951 there have been statistically significant increases in the number of heavy precipitation events (e.g., above the 95th percentile) in more regions than there have been statistically significant decreases, but there are strong regional and subregional variations in the trends**. In particular, many regions present statistically non-significant or negative trends, and, where seasonal changes have been assessed, there are also variations between seasons (e.g., more consistent trends in winter than in summer in Europe). The overall most consistent trends towards heavier precipitation events are found in central North America (very likely increase) but assessment for Europe shows likely increases in more regions than decreases.

AR6 (p. 1560)

In North America, there is robust evidence that the magnitude and intensity of extreme precipitation has *very likely* increased since the 1950s. Both [one-day maxima] and [5-day maxima] have significantly increased in North America during 1950-2018 (Sun et al., 2020, also Figure 11.13). There is, however, regional diversity. In Canada, there is a lack of detectable trends in observed annual maximum daily (or shorter duration) precipitation (Shephard et al., 2014; Mekis et al., 2015; Vincent et al., 2018).

NCA17 pp. 213-14:

Detectability of trends (compared to internal variability) for a number of precipitation metrics over the continental United States has been examined; **however, trends identified for the U.S. regions have not been clearly attributed to anthropogenic forcing**. One study concluded that increasing precipitation trends in some north-central U.S. regions and the extreme annual anomalies there in 2013 were at least partly attributable to the combination of anthropogenic and natural forcing... **Based on current evidence, it is concluded that detectable but not attributable increases in mean precipitation have occurred over parts of the central United States**. Formal detection-attribution studies indicate a human contribution to extreme precipitation increases over the continental United States, but confidence is *low* based on those studies alone due to the short observational period, high natural variability, and model uncertainty.

In summary, based on available studies, it is concluded that for the continental United States there is *high confidence* in the detection of extreme precipitation increases, while there is *low confidence* in attributing the extreme precipitation changes purely to anthropogenic forcing.

8.2.6 Tornadoes and severe convective storms

IPCC AR6 Sct. 11.7.3, p. 1594

Severe convective storms are convective systems that are associated with extreme phenomena such as tornadoes, hail, heavy precipitation (rain or snow), strong winds, and lightning.

The assessment of changes in severe convective storms in SREX (Chapter 3, Seneviratne et al., 2012) and AR5 (Chapter 12, Collins et al., 2013) is limited and focused mainly on tornadoes and hail storms. The SREX assessed that **there is *low confidence* in observed trends in tornadoes and hail** because of data inhomogeneities and inadequacies in monitoring systems. Subsequent literature assessed in the Climate Science Special Report (Kossin et al., 2017) led to the assessment of the observed tornado activity over the 2000s in the USA, with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days (*medium confidence*). However, **there is *low confidence* in past trends for hail and severe thunderstorm winds**. Climate models consistently project environmental changes that would support an increase in the frequency and intensity of severe thunderstorms that combine tornadoes, hail, and winds (*high confidence*), but there is *low confidence* in the details of the projected increase.

... In summary, because the definition of severe convective storms varies depending on the literature and the region, it is not straightforward to make a synthesizing view of observed trends in severe convective storms in different regions. In particular, **observational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected** due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant, but their variability of occurrence has increased since the 1970s, particularly over the 2000s, with **a decrease in the number of days per year, and an increase in the number of tornadoes on these days** (*high confidence*). Detected tornadoes have also increased in Europe, but the trend depends on the density of observations.

... In summary, **it is extremely difficult to detect and attribute changes in severe convective storms**. There is limited evidence that extreme precipitation associated with severe convective storms has increased in some cases.

8.2.7 Hurricanes and Tropical Cyclones

SREX (p. 159):

There have been no significant trends observed in global tropical cyclone frequency records, including over the present 40-year period of satellite observations (e.g., Webster et al., 2005). Regional trends in tropical cyclone frequency have been identified in the North Atlantic, but the fidelity of these trends is debated (Holland and Webster, 2007; Landsea, 2007; Mann et al., 2007a). Different methods for estimating undercounts in the earlier part of the North Atlantic tropical cyclone record provide mixed conclusions (Chang

and Guo, 2007; Mann et al., 2007b; Kunkel et al., 2008; Vecchi and Knutson, 2008). Regional trends have not been detected in other oceans (Chan and Xu, 2009; Kubota and Chan, 2009; Callaghan and Power, 2011). **It thus remains uncertain whether any observed increases in tropical cyclone frequency on time scales longer than about 40 years are robust**, after accounting for past changes in observing capabilities (Knutson et al., 2010).

AR5 (pp. 216-17):

Current data sets indicate no significant observed trends in global tropical cyclone frequency over the past century and it remains uncertain whether any reported long-term increases in tropical cyclone frequency are robust, after accounting for past changes in observing capabilities (Knutson et al., 2010). **No robust trends in annual numbers of tropical storms, hurricanes and major hurricanes counts have been identified** over the past 100 years in the North Atlantic basin. Measures of land-falling tropical cyclone frequency (Figure 2.34) are generally considered to be more reliable than counts of all storms which tend to be strongly influenced by those that are weak and/or short lived. Callaghan and Power (2011) find a statistically significant decrease in Eastern Australia land-falling tropical cyclones since the late 19th century although including 2010/2011 season data this trend becomes non-significant (i.e., a trend of zero lies just inside the 90% confidence interval). Significant trends are not found in other oceans on shorter time scales (Chan and Xu, 2009; Kubota and Chan, 2009; Mohapatra et al., 2011; Weinkle et al., 2012), although Grinstead et al. (2012) find a significant positive trend in eastern USA using tide-gauge data from 1923–2008 as a proxy for storm surges associated with land-falling hurricanes. Differences between tropical cyclone studies highlight the challenges that still lie ahead in assessing long-term trends.

In summary, this assessment does not revise the SREX conclusion of *low confidence* that any reported long-term (centennial) increases in tropical cyclone activity are robust, after accounting for past changes in observing capabilities. More recent assessments indicate that **it is unlikely that annual numbers of tropical storms, hurricanes and major hurricanes counts have increased over the past 100 years in the North Atlantic basin**. Evidence, however, is for a virtually certain increase in the frequency and intensity of the strongest tropical cyclones since the 1970s in that region.

AR6 (p. 1585)

There is low confidence in most reported long-term (multidecadal to centennial) trends in TC frequency- or intensity-based metrics due to changes in the technology used to collect the best-track data. This should not be interpreted as implying that no physical (real) trends exist, but rather as indicating that either the quality or the temporal length of the data is not adequate to provide robust trend detection statements, particularly in the presence of multidecadal variability.

There are previous and ongoing efforts to homogenize the best-track data (Elsner et al., 2008; Kossin et al., 2013, 2020; Choy et al., 2015; Landsea, 2015; Emanuel et al., 2018) and there is substantial literature that finds positive trends in intensity-related metrics in the best-track during the “satellite period”, which is generally limited to the past ~40 years (Kang and Elsner, 2012; Kishtawal et al., 2012; Kossin et al., 2013, 2020; Mei and Xie, 2016; Zhao et al., 2018; Tauvale and Tsuboki, 2019). **When best-track trends are tested using homogenized data, the intensity trends generally remain positive, but are smaller in amplitude** (Kossin et al., 2013; Holland and Bruyère, 2014). **Kossin et al. (2020) extended the homogenized TC intensity record to the period 1979–2017 and identified significant**

global increases in major TC exceedance probability of about 6% per decade.³ In addition to trends in TC intensity, there is evidence that TC intensification rates and the frequency of rapid intensification events have increased within the satellite era (Kishtawal et al. 2012; Balaguru et al., 2018; Bhatia et al., 2018). The increase in intensification rates is found in the best-track as well as the homogenized intensity data.

A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows no trend in the frequency of U.S. landfall events (Knutson et al., 2019).

8.2.8 Droughts

US NCA17 REPORT (Ch. 8, Wehner et al. 2017)

p. 231:

Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (very high confidence). **While by some measures drought has decreased over much of the continental United States in association with long-term increases in precipitation, neither the precipitation increases nor inferred drought decreases have been confidently attributed to anthropogenic forcing.**

The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures. (*High confidence*)

p. 233:

Drought is, of course, directly connected to seasonal precipitation totals. Figure 7.1 shows detectable observed recent changes in seasonal precipitation. In fact, the increases in observed summer and fall precipitation are at odds with the projections in Figure 7.5. **As a consequence of this increased precipitation, drought statistics over the entire CONUS have declined.**

SREX (p. 170)

From a paleoclimate perspective recent droughts are not unprecedented, with severe ‘megadroughts’ reported in the paleoclimatic record for Europe, North America, and

³ The **underlined** text referenced a study (Kossin et al. 2020) that later retracted a portion of its findings. Those authors assembled a data set on global TC incidence spanning 1979 to 2017 from which they claimed that the global fraction of TCs reaching major status (Cat 3—5) rose from 27% during 1979-1997 to 31% during 1998-2017 and that the increase was statistically significant. However, closer examination of their results showed a significant increase only in the North Atlantic (18% to 34%) whereas changes in all other basins (Eastern Pacific, Western Pacific, North Indian, South Indian, South Pacific) were not statistically significant. In a subsequent correction (<https://www.pnas.org/doi/10.1073/pnas.2021573117>), Kossin et al. stated that the global probability of observing a major TC rose from 34% during 1979-1997 to 37% in the later period and that the evidence for statistical significance was now weaker. Nevertheless, the authors claimed that the correction did not affect their conclusions.

Australia (Jansen et al., 2007). Recent studies extend this observation to African and Indian droughts (Sinha et al., 2007; Shanahan et al., 2009): much more severe and longer droughts occurred in the past centuries with widespread ecological, political, and socioeconomic consequences. Overall, these studies confirm that in the last millennium several extreme droughts have occurred (Breda and Badeau, 2008; Kallis, 2008; Büntgen et al., 2010).

In North America, there is *medium confidence* that there has been an overall slight tendency toward less dryness (wetting trend with more soil moisture and runoff; Table 3-2), although analyses for some subregions also indicate tendencies toward increasing dryness. This assessment is based on several lines of evidence, including simulations with different hydrological models as well as PDSI and CDD estimates (Alexander et al., 2006; Andreadis and Lettenmaier, 2006; van der Schrier et al., 2006a; Kunkel et al., 2008; Sheffield and Wood, 2008a; Dai, 2011).

The most severe droughts in the 20th century have occurred in the 1930s and 1950s, where the 1930s Dust Bowl was most intense and the 1950s drought most persistent (Andreadis et al., 2005) in the United States, while in Mexico the 1950s and late 1990s were the driest periods. Recent regional trends toward more severe drought conditions were identified over southern and western Canada, Alaska, and Mexico, with subregional exceptions (Dai, 2011).

SREX (p. 172)

Overall, though new studies have furthered the understanding of the mechanisms leading to drought, there is still relatively limited evidence to provide an attribution of observed changes, in particular given the issues associated with the availability of observational data (Section 3.2.1) and the definition and computation of drought indicators (Box 3-3). This latter point was mostly identified in post-AR4 studies (Box 3-3). Moreover, regions where consistent increases in drought are identified (see ‘Observed Changes’) are only partly consistent with those where projections indicate an enhancement of drought conditions in coming decades (see next paragraphs). We thus assess that there is *medium confidence* (see also Section 3.1.5) that anthropogenic influence has contributed to some changes in the drought patterns observed in the second half of the 20th century, based on its attributed impact on precipitation and temperature changes (though temperature can only be indirectly related to drought trends; see Box 3-3). However **there is *low confidence* in the attribution of changes in droughts at the level of individual regions.**

AR5 (pp. 214-215)

Based on evidence since AR4, SREX concluded that there were not enough direct observations of dryness to suggest high confidence in observed trends globally, although there was *medium confidence* that since the 1950s some regions of the world have experienced more intense and longer droughts. The differences between AR4 and SREX are due primarily to analyses post-AR4, differences in how both assessments considered drought and updated IPCC uncertainty guidance.

Because drought is a complex variable and can at best be incompletely represented by commonly used drought indices, discrepancies in the interpretation of changes can result. For example, Sheffield and Wood (2008) found decreasing trends in the duration, intensity and severity of drought globally. Conversely, Dai (2011a,b) found a general global increase in drought, although with substantial regional variation and individual events dominating trend signatures in some regions (e.g., the 1970s prolonged Sahel drought and the 1930s drought

in the USA and Canadian Prairies). Studies subsequent to these continue to provide somewhat different conclusions on trends in global droughts and/or dryness since the middle of the 20th century (Sheffield et al., 2012; Dai, 2013; Donat et al., 2013c; van der Schrier et al., 2013).

In summary, the current assessment concludes that there is not enough evidence at present to suggest more than *low confidence* in a global-scale observed trend in drought or dryness (lack of rainfall) since the middle of the 20th century, owing to lack of direct observations, geographical inconsistencies in the trends, and dependencies of inferred trends on the index choice. Based on updated studies, AR4 conclusions regarding global increasing trends in drought since the 1970s were probably overstated. However, it is *likely* that the frequency and intensity of drought has increased in the Mediterranean and West Africa and decreased in central North America and north-west Australia since 1950.

AR6 (Drought, Observed trends, Section 11.6.2, pp. 1573-75)

p. 1573

Strong precipitation deficits have been recorded in recent decades in the Amazon (2005, 2010), south-western China (2009–2010), south-western North America (2011–2014), Australia (1997–2009), California (2014), the middle East (2012–2016), Chile (2010–2015), the Great Horn of Africa (2011), among others (van Dijk et al., 2013; Mann and Gleick, 2015; Rowell et al., 2015; Marengo and Espinoza, 2016; Dai and Zhao, 2017; Garreaud et al., 2017, 2020; Marengo et al., 2017; Brito et al., 2018; Cook et al., 2018). **Global studies generally show no significant trends in SPI time series** (Orlowsky and Seneviratne, 2013; Spinoni et al., 2014), **and in derived drought frequency and severity data** (Spinoni et al., 2019), with very few regional exceptions (Section 11.9 and Figure 11.17).

p. 1574

For AR6 regions, several studies suggest an increase in the frequency and areal extent of soil moisture deficits, with examples in East Asia (Cheng et al., 2015; Y. Qin et al., 2015; Jia et al., 2018), Western and Central Europe (Trnka et al., 2015b), and the Mediterranean (Hanel et al., 2018; Moravec et al., 2019; Markonis et al., 2021). **Nonetheless, some analyses also show no long-term trends in soil drying in some AR6 regions – for example, in Eastern North America (Park Williams et al., 2017) and Central North America** (Seager et al., 2019), as well as in North Eastern Africa (Kew et al., 2021).

There is evidence based on streamflow records of increased hydrological droughts in East Asia (D. Zhang et al., 2018) and southern Africa (Gudmundsson et al., 2019). **In areas of Western and Central Europe and Northern Europe, there is no evidence of changes in the severity of hydrological droughts since 1950** based on flow reconstructions (Caillouet et al., 2017; Barker et al., 2019) and observations (Vicente-Serrano et al., 2019). **In North America, depending on the methods, datasets and study periods, there are differences between studies that suggest an increase (Shukla et al., 2015; Udall and Overpeck, 2017) versus a decrease in hydrological drought frequency (Mo and Lettenmaier, 2018), but in general there is strong spatial variability** (Poshtiri and Pal, 2016). Streamflow observation reference networks of near-natural catchments have also been used to isolate the effect of climate trends on hydrological drought trends in a few regions, but these show limited trends in Northern Europe and Western and Central Europe (Stahl et al., 2010; Bard et al., 2015; Harrigan et al., 2018), North America (Dudley et al., 2020) and most of Australia, with the exception of Eastern and Southern Australia (X.S. Zhang et al., 2016).

p. 1575

Few AR6 regions show observed increases in meteorological drought (Section 11.9), mostly in Africa and South America (NES: *high confidence*; WAF, CAF, ESAF, SAM, SWS, SSA, SAS: *medium confidence*); a few others show a decrease (WSB, ESB, NAU, CAU, NEU, CNA: *medium confidence*). There are stronger signals indicating observed increases in agricultural and ecological drought (Section 11.9), which highlights the role of increased [evapotranspiration], driven by increased [Atmospheric Evaporative Demand], for these trends (Sections 11.6.2.3, 11.6.2.5). Past increases in agricultural and ecological droughts are found on all continents and several regions (WAF, CAF, WSAF, ESAF, WCA, ECA, EAS, SAU, MED, WCE, NES: *medium confidence*), while decreases are found only in one AR6 region (NAU: *medium confidence*). The more limited availability of datasets makes it more difficult to assess historical trends in hydrological drought at regional scale (Section 11.9). Increasing (MED: *high confidence*; WAF, EAS, SAU: *medium confidence*) and decreasing (NEU, SES: *medium confidence*) trends in hydrological droughts have only been observed in a few regions.

AR6 on Attribution (p. 1577)

There are only two AR6 regions in which there is at least *medium confidence* that human-induced climate change has contributed to changes in meteorological droughts (Section 11.9). In South-western South America (SSW), there is *medium confidence* that human-induced climate change has contributed to an increase in meteorological droughts (Boisier et al., 2016; Garreaud et al., 2020), while in Northern Europe (NEU), there is *medium confidence* that it has contributed to a decrease in meteorological droughts (Gudmundsson and Seneviratne, 2016) (Section 11.9). **In other AR6 regions, there is inconclusive evidence in the attribution of long-term trends, but a human contribution to single meteorological events or subregional trends has been identified in some instances... In North America, the human influence on precipitation deficits is complex (Wehner et al., 2017), with low confidence in the attribution of long-term changes in meteorological drought in AR6 regions.**

8.3 Extreme weather trends at global and continental scale

8.3.1 Tropical Cyclones (TCs)

Hurricane strength records for the North Atlantic and the Western Pacific go back to 1950 and the record does not show an increase in either total or major TCs. Figure 8.3.1 was published by Roger Pielke Jr. as an update to the Best Track data series originally presented in Weinkle et al. (2012).

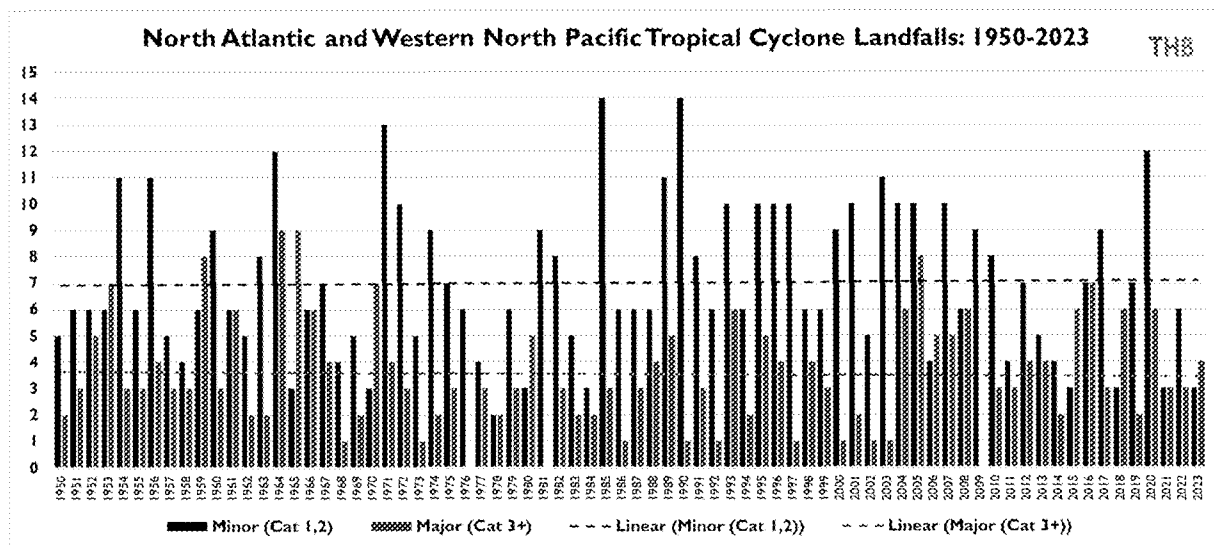


Figure 8.3.1. Tropical Cyclone Landfalls. Source: <https://rogerpielkejr.substack.com/p/global-tropical-cyclones>, Weinkle et al. (2012)

Similarly, Figure 8.3.2 (Maue 2025, <https://climatlas.com/tropical/>) shows that both all hurricanes and major hurricanes have not become more common since 1980, the period of rapidly growing human influences. In fact, both numbers have trended down slightly since the 1990s:

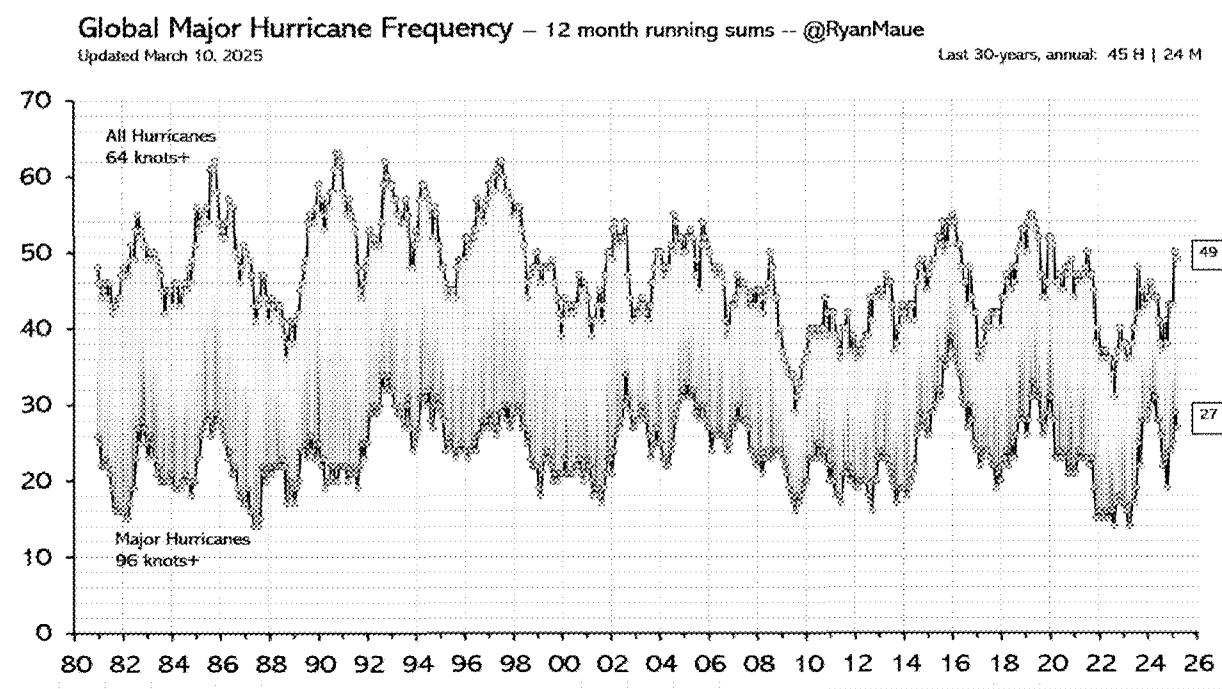


Figure 8.3.2: Global hurricane frequency. Source: Maue (2025)

A metric that combines the number, duration, and strength of TCs is the Accumulated Cyclone Energy (ACE) Index maintained at Colorado State University, shown in Figure 8.3.3. It clearly shows no long-term increase, in fact declining slightly since 1990.

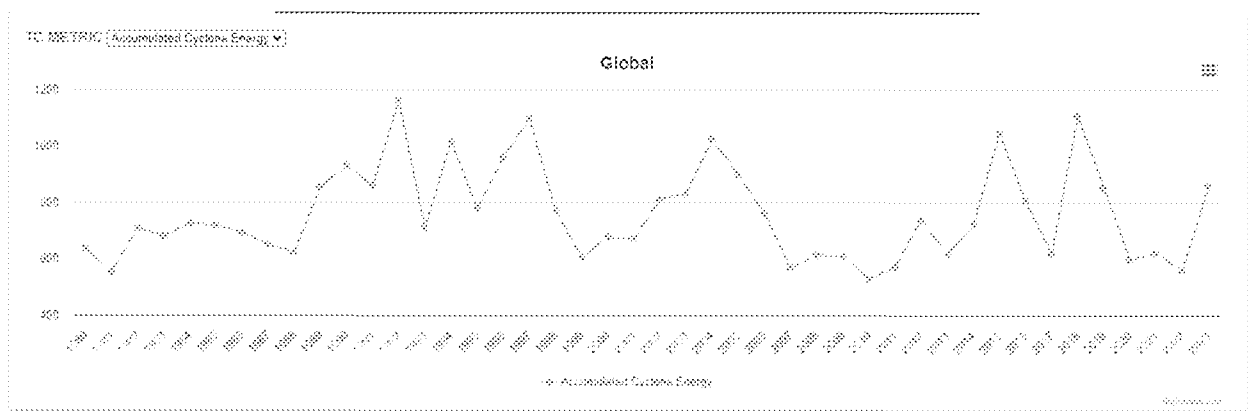


Figure 8.3.3: Global Accumulated Cyclone Energy. Source: Klotzbach (2025)
<https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=global>

Note that Tu et al. (2024) report that the Power Dissipation Index (PDI), another different measure that combines hurricane number, duration, and strength, has either remained unchanged or has declined in all global oceanic basins since the mid-1990s.

Today's global climate simulations are too coarse to project changes in TCs directly. Rather, projections are derived from finer “downscaled” simulations or proxies involving sea surface temperatures, winds, and aerosols. By those methods, a warming climate is expected to show declining hurricane formation rates. (Chand et al. 2022). Climate models also project fewer Tropical Cyclones under future global warming, and even though models project they will increase in strength, the annual averages of rainfall maxima decline (Stansfield et al. 2020).

8.3.2 Wildfires

As shown in Figures 8.3.4 and 8.3.5 global wildfire activity as measured by European Space Agency peaked over a decade ago and shows a downward trend since.

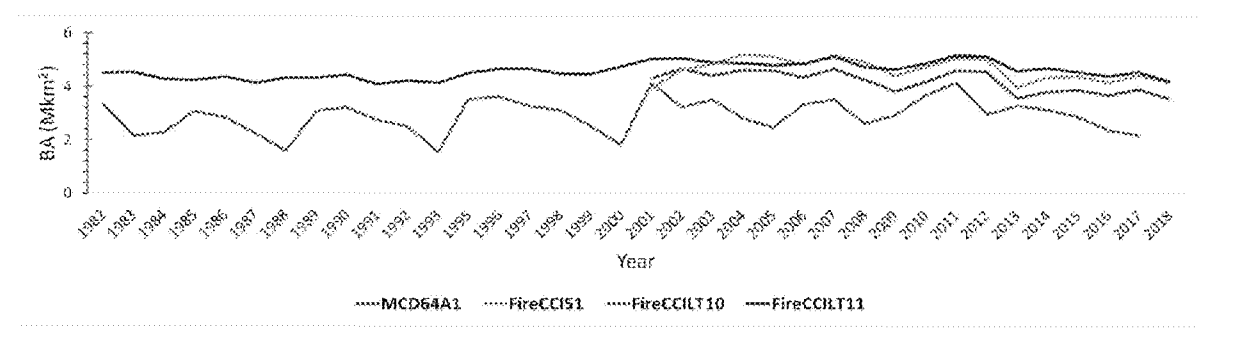


Figure 8.3.4: Global wildfire 1982-2018. Source: Copied from Oton et al. (2021). Note: the different coloured lines represent different data products based on satellites and algorithms used.

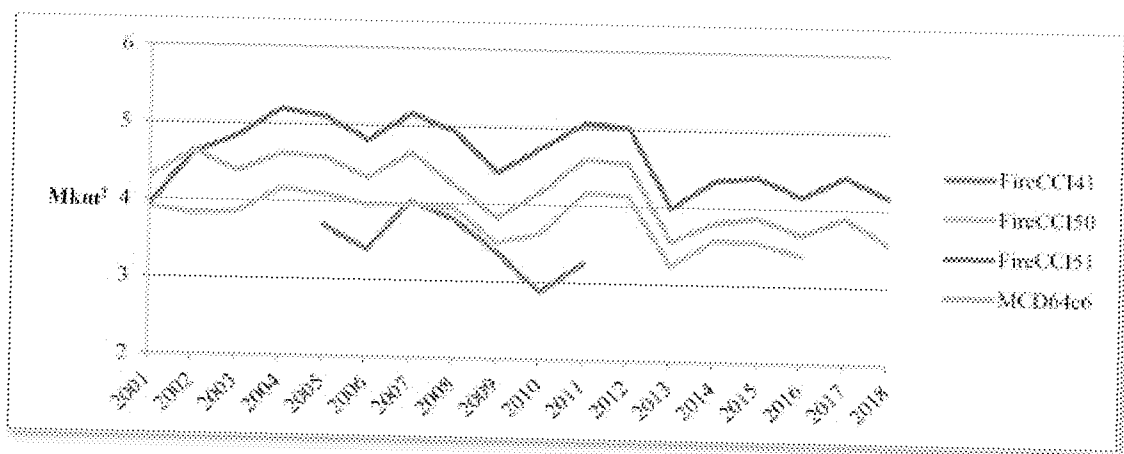


Figure 8.3.5: Global wildfire 2001-2018. Source: Copied from Lizundia-Loiola et al. (2021). Note: the different coloured lines represent different data products based on satellites and algorithms used

US data from the National Interagency Fire Centre (NIFC) from 1926 to 2023 are shown in Figure 8.3.6.

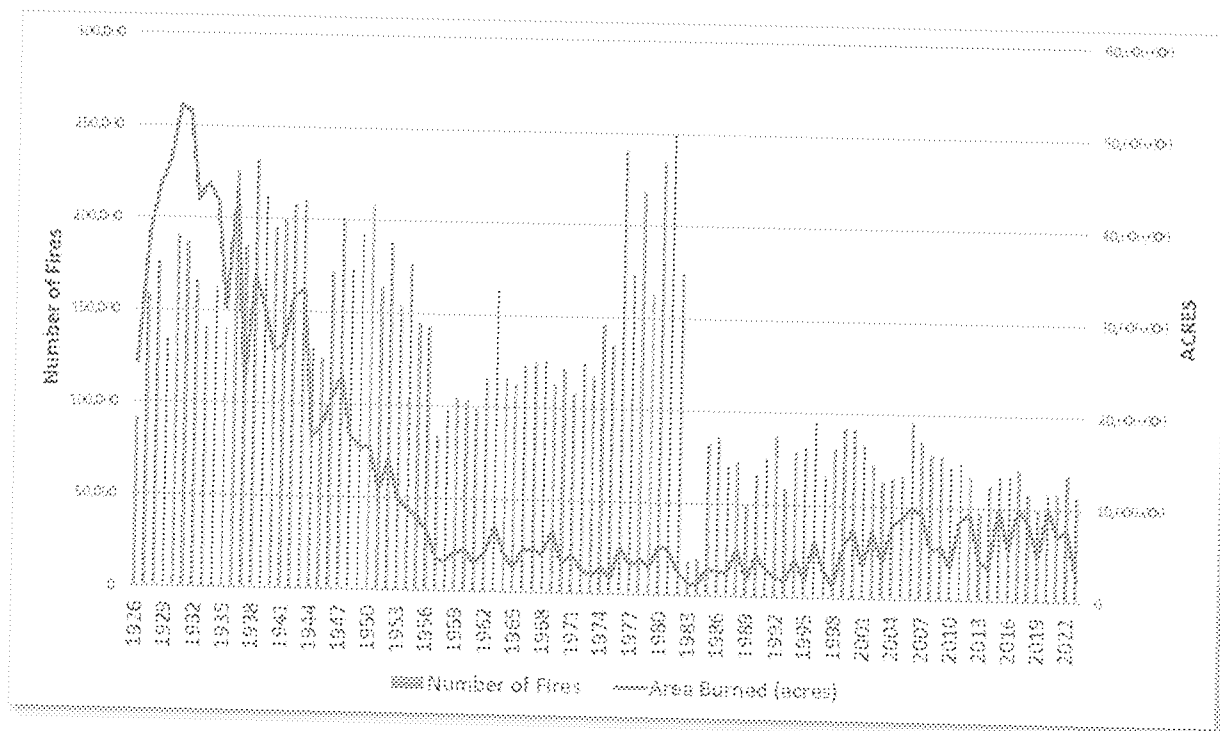


Figure 8.3.6: US wildfires 1926 to 2023. Source: National InterAgency Fire Centre data Pre-2017 (archived)

[https://web.archive.org/web/20200212033452/https://www.nifc.gov/fireInfo/fireInfo stats totalFires.html](https://web.archive.org/web/20200212033452/https://www.nifc.gov/fireInfo/fireInfo%20stats%20totalFires.html). 2018-2023: <https://www.nifc.gov/fire-information/statistics/wildfires>

Note the NIFC has removed the pre-1960 data from its current website. They claim it is because measurement methods changed after 1960. This explanation seems inadequate since agencies blend

temperature and extreme weather data series in other contexts when measurement systems changed. In this case if anything the measurement of wildfires has improved since the early 20th century so any bias will be towards understating early wildfire counts. Nonetheless just focusing on the post-1985 interval the number of fires is not increasing. The area burned did increase but only until about 2007.

It is difficult to establish a natural baseline for wildfire activity because of active fire suppression activity since 1900. Paleoclimatic evidence indicates, however, that past wildfire activity was much higher than at present. Marlon et al. (2012) used sedimentary charcoal layers to reconstruct fire history of western US for the past 1400 years. They also fit a model to predict expected fire activity as a function of climatic conditions. The results are summarized in Figure 8.3.7 below (from Figure 2 in their paper).

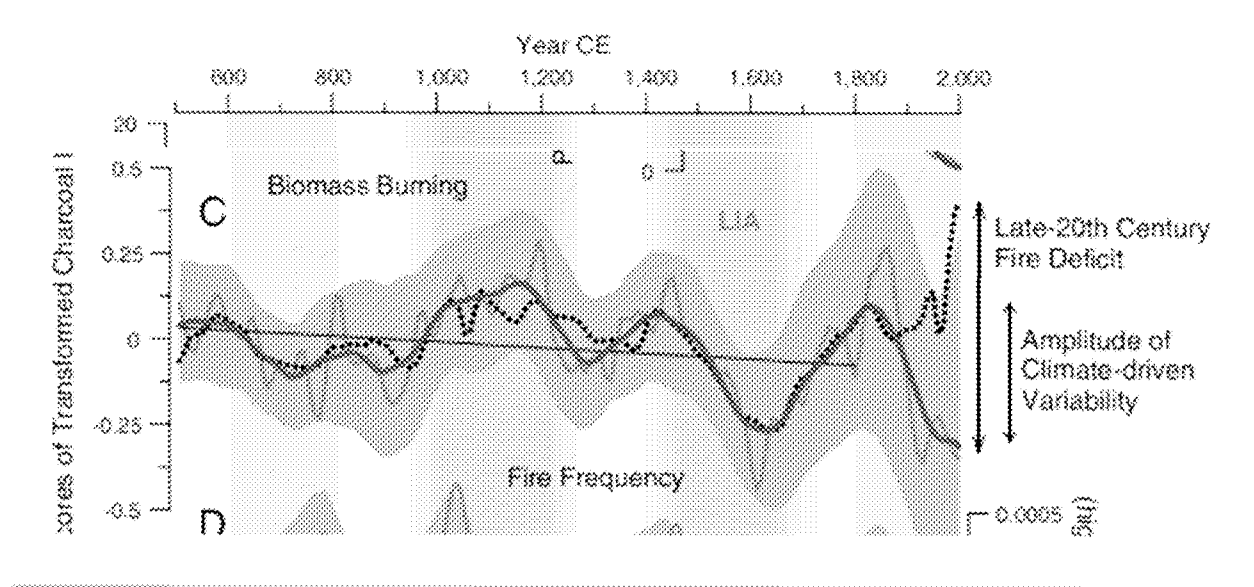


Figure 8.3.7: Fire frequency and fire deficit in the US. Source: Copied from Marlon et al. (2012)

In their figure the red line shows the smoothed charcoal record and the black dotted line shows the predicted charcoal record based on the statistical model. The gap at the end implies there has been a growing wildfire deficit over the 20th century. In other words, however much fire was observed in the 20th century it was less than what would have been observed in previous centuries based on the climatic conditions. Parks et al. (2025) likewise find that despite the recent increase in wildfire burn area in North America, a significant wildfire deficit remains relative to historical wildfire regimes.

8.3.3 Precipitation

Figure 8.3.8 shows that US long term data from NOAA shows an insignificantly increasing tendency toward extreme wetness (+0.001% per year)

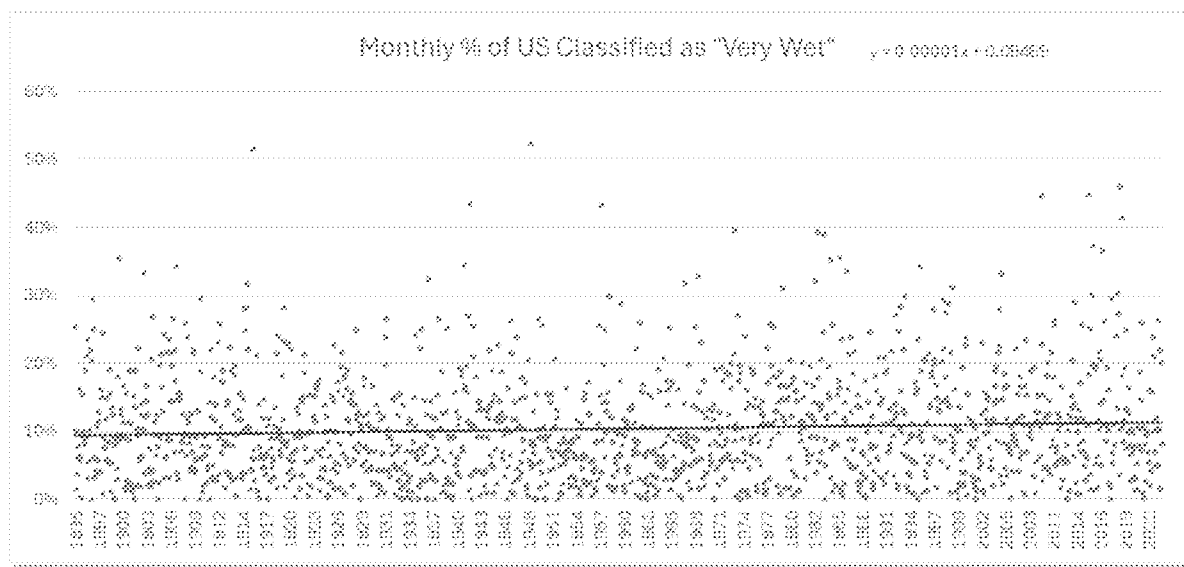


Figure 8.3.8: Long term US wetness (%). Source: NOAA
<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>

Precipitation will be discussed further in the review of CONUS data below.

8.3.4 Drought

As shown in Figure 8.3.9 US long term data (NOAA) shows an insignificantly declining tendency toward extreme dryness (-0.001% per year)

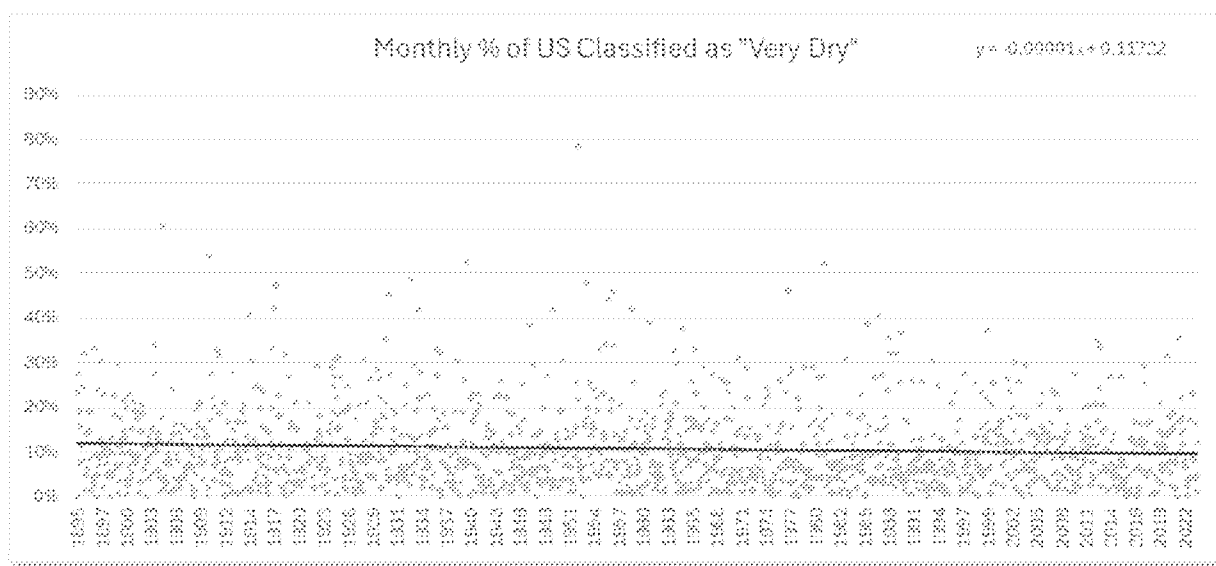


Figure 8.3.9: US dryness (%) 1895—2023. Source: NOAA
<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>

Kogan et al. (2020) examines a 38-year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change: “it is possible to state firmly that global and main grain countries’ drought area and intensity trends have not been following global climate warming since 1980’s.”

8.4 Temperature and precipitation extremes in the Contiguous US (CONUS)

8.4.1 CONUS daily temperatures are becoming less extreme

Daily maximum temperatures in the warm season (TMax, May-Sep) and daily minimum temperatures in the cold season (TMin, Dec-Mar) are available beginning in Dec 1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (Quinlan et al. 1987, Karl et al. 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although there are certainly errors in the dataset, with over 1,000 stations we can have relatively high confidence in any underlying signal that might be discovered.

We begin with the question of whether the occurrence of daily record high or low temperatures changed has changed since Dec 1898. Each warm-season has 153 days (1 May to 30 Sep) and each cold-season has 122 days (1 Dec to 31 Mar). For each station and day, we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time, the expected number of records for TMax would be 1.21 ($=153/126$) per station per year and for TMin 0.96 ($=122/126$) per station per year. Figure 8.4.1 indicates the observed distribution in time of the occurrence of these extreme events.

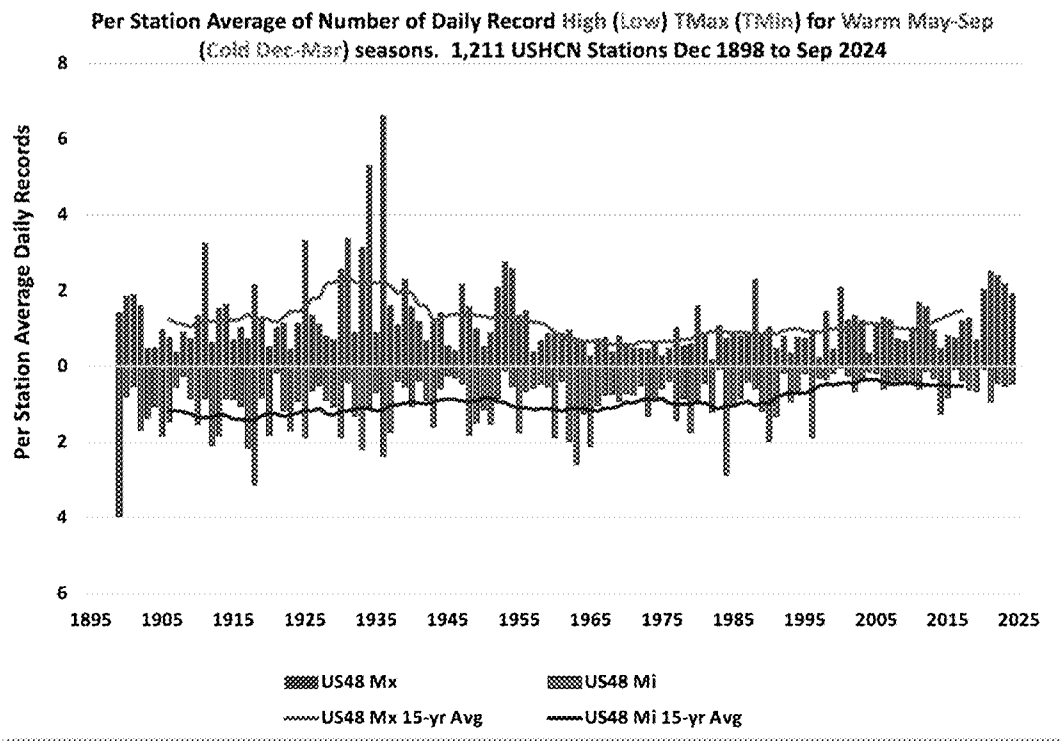


Figure 8.4.1 Number of daily record High (red) and Low (blue) for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92% of observations in the 126-year period since Dec 1898.

The results indicate a common feature in many metrics of warm-season extremes in the CONUS - the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. On a per-station average, 60% of the TMax records and 59% of the TMin records occurred in the first half of the period (1899-1961).

On the cold side, the Valentine's Day Arctic outbreak in Feb 1899 stands as the most extensive cold extreme experienced by the CONUS, with 1917 2nd. The frequency of cold records has declined, especially over the last quarter of the period in which only 13% of the extreme cold events were measured. In contrast, 25% of the extreme TMax records were achieved in the last quarter in accordance with statistical expectations. These general features have been noted in past assessments (IPCC AR5, IPCC AR6, NCA4, NCA5). Combining the two records the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 8.4.2. For each station and for each year the hottest warm season and coldest cold-season temperatures were calculated and converted to anomalies relative to the station's long term warm and cold season (respectively) averages. Then the differences between these were computed by station and geographically-averaged over all stations, thus yielding an annual measure of the expected range of local extreme temperatures for each year. Figure 8.11 shows the 15-year trailing average of this measure which has clearly declined over the past century.

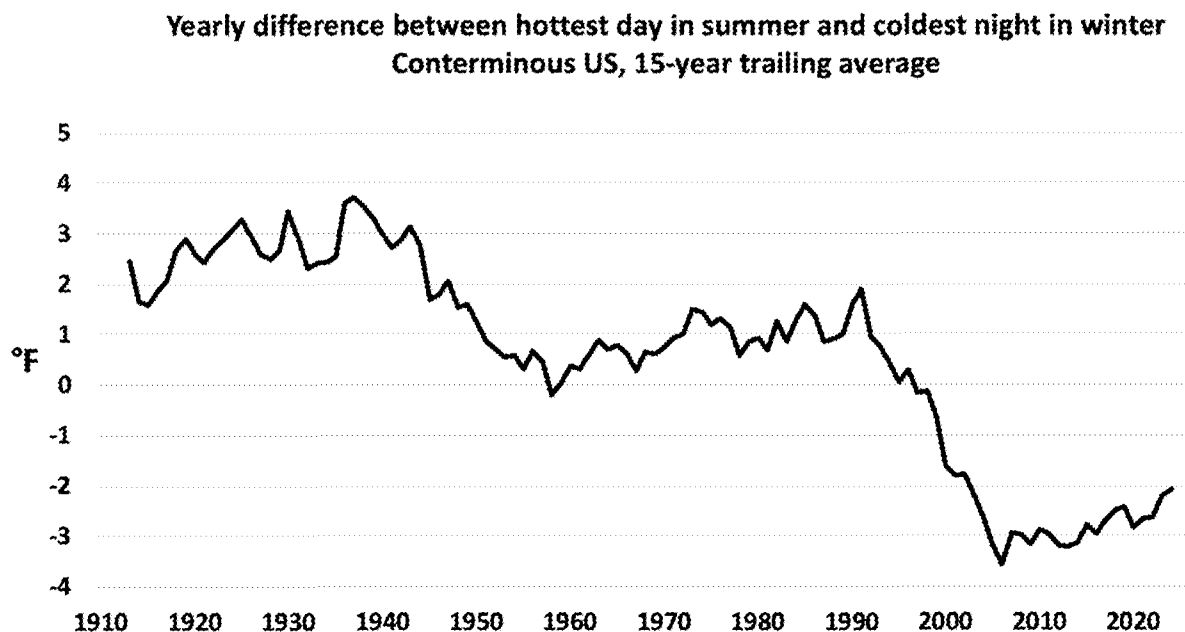


Figure 8.4.2. 15-year trailing average of the difference each year of each station's hottest warm-season TMax and coldest cold-season TMin relative to the long-term average.

The average difference for each station between the hottest summer TMax and coldest winter TMin has declined about 5°F in the past 126 years. The decline is due mostly to warming winter TMin, but a decline in the magnitude of summer TMax is also a factor. The rise in TMin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (Spencer et al. 2025).

Summarizing Figures 8.4.1 and 8.4.2, while temperature extremes are regularly experienced in the US and attract a great deal of media attention, long term records show the US climate has become less extreme over time (milder) when measured in terms of the range between warm season maxima and cold season minima.

8.4.2 Exceedances of a heat threshold

Under the heading of “The Risk of Temperature Extremes is Changing”, the most recent US National Climate Assessment report (NCA5) notes the increase in a threshold metric of number of days at or above 95°F, stating,

“The western US has been particularly affected by extreme heat since the 1980s ..., experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021.”

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS, threshold statistics can be misleading. A region with many stations that have near 95°F TMax average temperatures in the summer might see large swings in the metric when only small changes in average temperature occur. Elsewhere with stations that either rarely or virtually always achieve 95°F TMax temperatures, a small change will not impact the results much at all. In the past 126 years, the average CONUS station experienced 129 days exceeding 95°C per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, one needs to view such threshold analyses with caution.

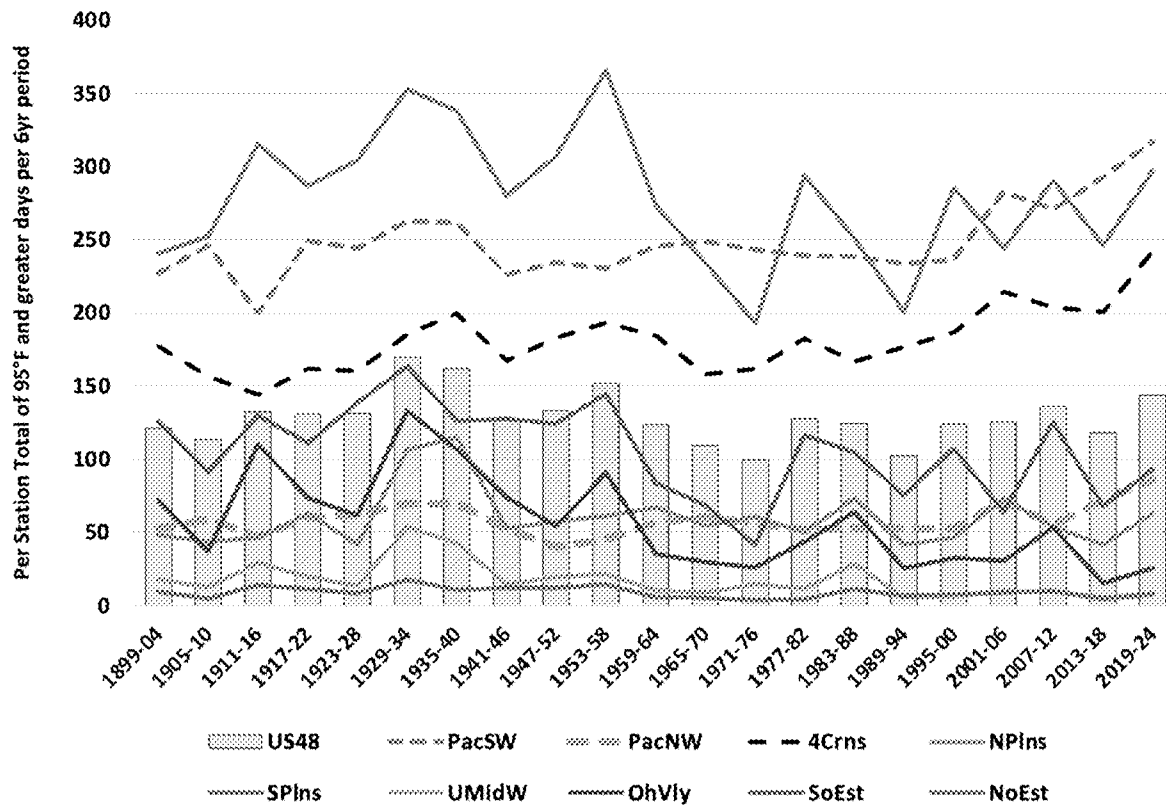


Figure 8.4.3. Total number of days $\geq 95^{\circ}\text{F}$ in 6-yr periods, US 48 (bars) and regions (lines).

In Fig. 8.4.3 we see that only three of the nine regions, all in the West, have experienced upward trends in the number of 95°F or hotter days (dashed lines). The CONUS as a whole has not and the other six regions have experienced declines.

The Pacific NW heatwave of 2021 is referenced as of the NCA5 claim, an event we examine more closely in Section 6.4. The evidence indicates it was a “black swan” event; *i.e.*, a single, unprecedented event in the record, not part of a pattern of increasing extreme heat. For example, the 5-day average tropospheric grid-point temperature anomaly over the Pacific NW during that event was $+10.8^{\circ}\text{C}$, the most extreme NH grid point summer anomaly in the 46 years from over 4 million grids. In contrast, the global anomaly during that time was virtually zero ($+0.03^{\circ}\text{C}$, Mass et al. 2024).

The heading “The Risk of Temperature Extremes is Changing” suggests positive trends are now being observed in threshold temperatures on a widespread basis, but that is not evidenced in the combined CONUS results of the figures above.

8.4.3 Heatwaves

Heatwaves (consecutive days that exceed an extreme threshold) have a greater societal impact than a single daily record. We measure “Heatwave Days” here as the count of all days in May-Sep each year that exceed the 90th percentile and that lie within a run of at least six consecutive days. This is equivalent to the method used in NCA5 except that the reference period here is the entire record 1899-2024 while NCA5 truncated the reference period to 1961-1990, a cool time. That truncation

boosts positive results (days exceeding the 90th percentile) in periods warmer than the reference period, especially starting in 1960 and moving to the present (see *Urban Influences* below).

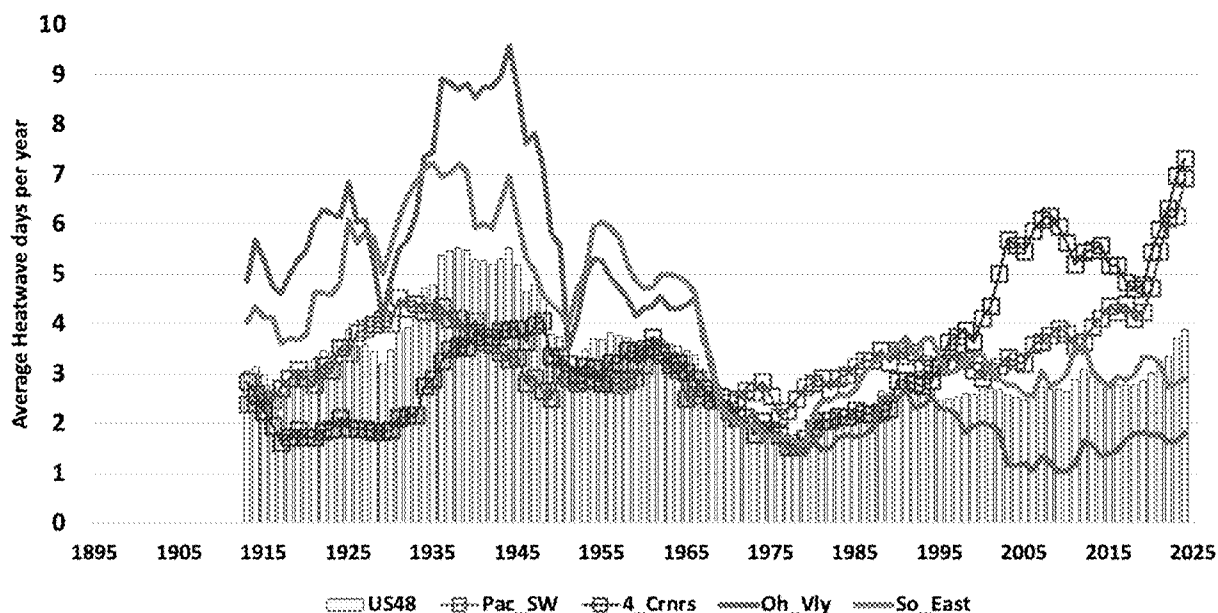


Figure 8.4.4 15-year trailing average of number of heatwave days per year per station in the CONUS (bars) and four regions: Pac_SW (purple squares, CA, NV), 4_Crnrs (red squares, AZ,NM,UT,CO), Oh_Vly (blue, MO, IL, KY, TN, IN, OH, WV) and So_East (green, MS, AL, GA, FL, SC, NC, VA).

Figure 8.4.4 indicates again the excessive heat of the first half of the 20th century, primarily in the eastern two-thirds of the nation, as seen in the regional values for the Ohio Valley and the Southeast as examples. The West has seen a recent increase of heatwave days and the two regions with the highest number are shown, the Pacific Southwest and the Four-Corners (NCA5). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20th century, but in the 21st century the patterns have favored heatwaves in the West. For CONUS as a whole, heatwaves are no more common today than they were a century ago.

Of interest here is the regional variation of this metric. The four northern regions (Pacific NW, Northern Plains, Upper Midwest, and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains, Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

Urban influences

The NCA5 directs readers to the website <https://www.globalchange.gov/indicators/heat-waves> (USGCRP 2023) to view the number of urban heatwaves by decade from the 1960s. The figure shows a monotonic increase in each decade from 2 occurrences per year in the 1960s to 6 in the 2020s. The definition of a heatwave is an unusual but practical measure of human discomfort - a period of at

least 2 consecutive days when the minimum apparent temperature (combination of temperature and humidity) exceeds the 85th percentile. Note too, the dataset is limited to the 50 largest U.S. cities.

These increasing values since 1960 presented in USGCRP (2023) are entirely reasonable, but are unrelated to GHG emissions for at least two reasons. Urbanization in these cities is a major factor in the rise of TMin relative to co-located TMax and relative to TMin at rural stations. Also, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. This does not dismiss the real rise in nighttime temperatures in major U. S. cities and the societal impacts associated with these changes. However, we note for a variety of reasons, that summer TMax (especially in rural areas) serves as better response variable for detecting potential changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs (Christy et al. 2009). For the CONUS as a whole, the evidence in this section suggests GHG emissions have had little-to-no effect on heatwaves.

8.4.4 Extremes in daily precipitation.

Because precipitation involves a discrete phase change (water vapor to liquid), it is stochastic and episodic in character and requires careful statistical treatment to understand variability over long time periods (see *8.1 Introduction*). The US National Climate Assessments (NCA4, NCA5) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of the CONUS, especially the Northeast, when starting in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in extreme events are in the Northeast and the smallest in the West, a trend counter to the changes in temperature extremes.

McKittrick and Christy (2019) examined long-term and consistent station observations of daily precipitation to test some of these NCA claims for the Southeast and West Coast. When the time series were extended back in time (as far as 1872 in some cases) or when starting later (1978), there were no significant trends for either region. For this report we updated these findings with similarly constructed observations from 29 stations on the Pacific Coast (1893ff from San Diego CA to Blaine WA), 24 stations in the humid Southeast (1872ff from Austin TX to Washington DC), and 21 stations in the Northeast (1888ff from Buffalo NY to Gardiner ME). The results were as follows.

Pacific region:

- Average precipitation trend is significant (downwards) in Astoria, insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Big Sur, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Aberdeen and Big Sur and negative and significant in Newport (insignificant elsewhere).
- Averaged over all stations in the region none of these three trend parameters is statistically significant.

Southeast region:

- The trend in average precipitation is positive and significant in Mobile and Quitman, insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Mobile, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Vicksburg and Norfolk, insignificant elsewhere.
- Averaged over all stations in the region none of these three trend parameters is statistically significant

Northeast region:

- The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall.
- The trend in rainfall variance is positive and significant in Portland, Albany and Buffalo, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Portland and Gardiner, insignificant elsewhere.
- Averaged over all stations in the region the trend parameters for variance and maximum precipitation are not statistically significant.

Pacific Coast heavy rainfall events

The Pacific Coast receives considerable precipitation from Atmospheric River (AR) events which often last more than a day or two (e.g., Gershunov et al. 2017, Pan et al. 2024). The worst-known such event in recent history was the ArkStorm that occurred between December 1861 and January 1862, which dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 15 feet of water (Brewer 1930, Null and Hulbert 2007). Paleoclimate research has found six megastorms more severe than 1861–1862 in California during the last 1800 years, occurring at intervals of 300 years or so (Porter et al. 2011).

SIDEBAR: Perils of short data records

San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 8.2.

Event	Record (inches)	Year
3-day	6.94	2023
5-day	8.55	2023
14-day	12.62	2023
30-day	18.93	1998

Table 8.2: Extreme rainfall records, San Francisco, 1895-2024.

The records all cluster in the more recent data. 2023 appears to be an exceptional year and since it is near the end of the sample it might suggest that the climate has shifted into a more hazardous state, perhaps as a result of human influences.

But the picture is very different if we use a sample that begins 45 years earlier, in 1850. Table 8.3 shows that the record-setting events then all happened in the 1860s. Furthermore 2023 is now not even in 2nd place but falls to 3rd or 4th. Also, comparing the records of the two charts the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1998 and 2023 events, with 14- and 30-day totals about 50 percent higher.

Event	Record (inches)	Year	Rank of 130-yr extreme
3-day	8.85	1867	3
5-day	9.80	1867	3

14-day	19.05	1862	4
30-day	28.25	1862	2

Table 8.3: Extreme rainfall records, San Francisco, 1850-2024.

The range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter et al. (2011) discovered that in the past 1,800 years at least six megastorms were more intense than the devastating 1861-62 ArkStorm that struck the region. Evidently such extreme events have impacted the region about every 300 years, though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability in general and of extreme events in particular. Accurate representation of the full range of natural variability is necessary for any attribution analyses (see 6.4). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time-sample of 130 years provides an underestimation of the extreme value by up to 50% determined when adding only 45 more years of observations. Compared to millennial-scale paleoclimate evidence, an even greater underestimation would occur. An important lesson is that the climate can deliver great surprises on its own, even without human influences.

We examine occurrences of 5-day deluges as follows. In a 130-year span there are 26 5-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values. A single year may have more than one of the 26 heaviest. Each of those can be thought of as 1-in-5yr events. If there are no trends in precipitation then the total number of these events across all stations should be evenly spread out over the years. In Fig. 8.4.5 we show the distribution in time of these events. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of these types of precipitation metrics, there is no indication of a tendency to become more frequent over time.

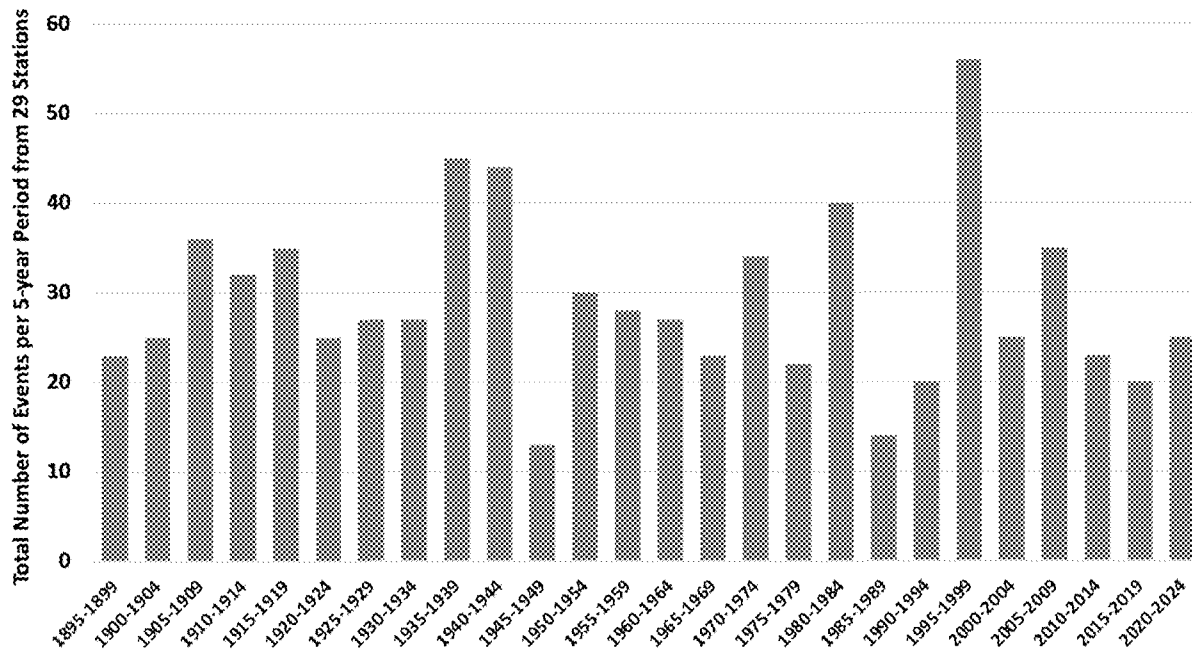


Figure 8.4.5. The time distribution by 5-year periods of the 26 heaviest occurrences for each station (i.e., nominal 1-in-5 year event).

Southeast heavy rainfall events

The temporal pattern of 5-day totals of the 1-in-5yr heavy events in the humid Southeast (Figure 8.4.6) is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA4 and NCA5 of a tendency for an increasing frequency of heavy events, due to a temporal clustering of tropical storms from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events.

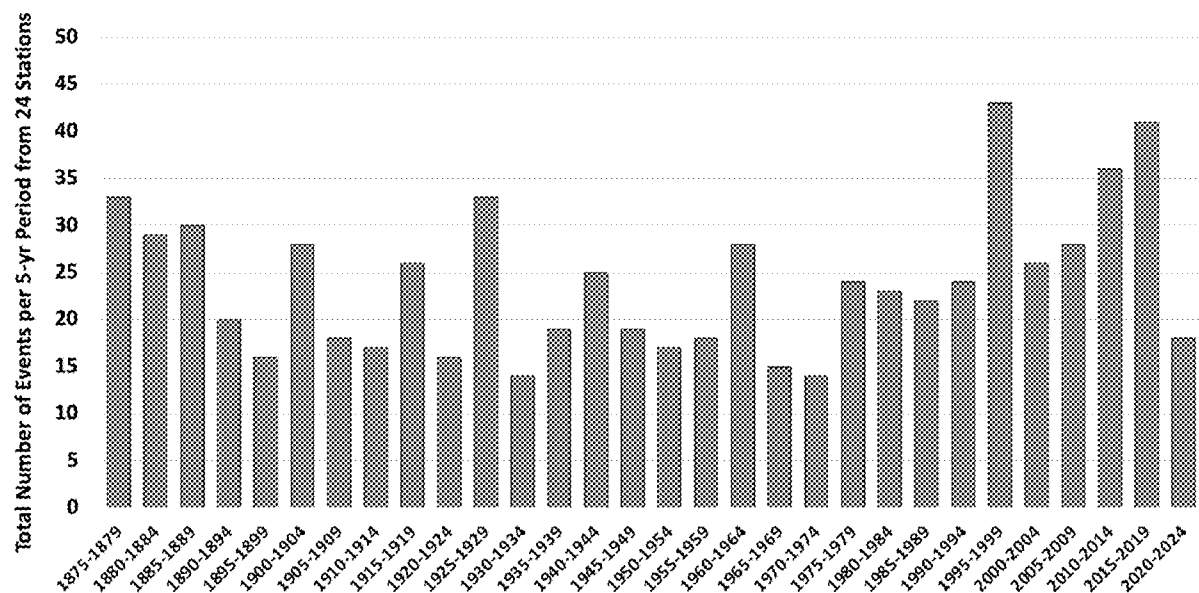


Figure 8.4.6. As above but for the 30 heaviest 1-in-5yr events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1875-2024.

Northwest heavy rainfall events

Fig. 8.4.7 shows the 27 (1-in-5yr) heaviest 3-day events for the last 135 years in 21 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest variations in time. In this region, 72% of the events occur during June to October and are dominated by tropical incursions of hurricanes, tropical storms or tropical storms that transition to extratropical systems. According to NCA4 and NCA5 this region experienced the largest increases in extreme events, so it shall be examined more closely.

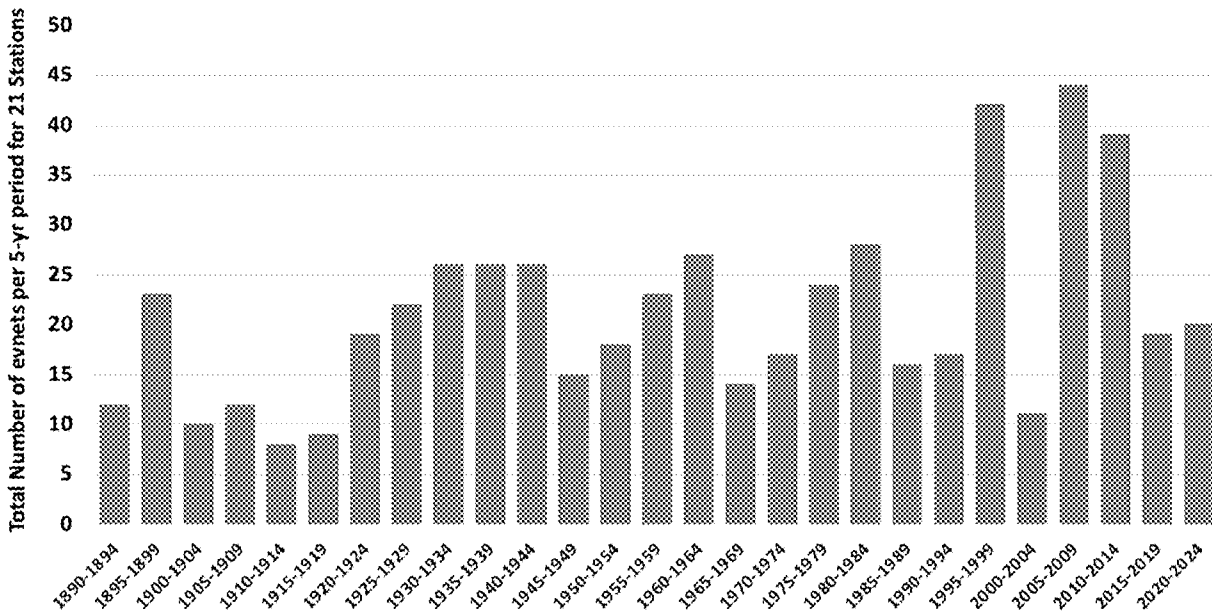


Figure 8.4.7. Time distribution of the heaviest 27 (1-in-5yr) heaviest 3-day precipitation events for 21 stations from NY to ME, including Montreal.

Howarth et al. (2019) report differences in the Northeast between two 18-year periods: 1979-96 and 1997-2014 (a similar region as in Fig. 8.16 that includes PA and NJ) of various precipitation extremes. One metric which indicated a dramatic increase (317%) was found for 24-hr events > 6 inches. This high increase is due to the very small numbers of such events of which there were only 6 in the first period and 25 in the second as reported for 58 stations. This high percentage increase is due to the very small numbers of the events; only 6 in the first period and 25 in the second. Most of the stations, did not record such an event suggesting these erratic, episodic events over brief, 18-yr periods, need scrutiny by additional statistical methods.

Using the information in Fig. 8.4.7 over the same years as Howarth et al. we find a 51% increase in the frequency of heavy events between the two periods. One can see in Fig. 8.16 that it was unfortunate that Howarth et al. ended in 2014 prior to a return to the long-term average of such events.

A feature of Howarth et al. is the use of single day totals which is questionable because extreme events are often spread across the time-of-observation boundary. Thus stations measuring at 0700 LT versus those at Midnight will have differing results for a particular event which would then have major impacts on counting these events. We use the 3-day totals in Fig. 8.4.7 to be sure to capture the extent of these extreme downpours. In any case, we can confirm that the period 1997 to 2014 experienced a cluster of heavier events as Howarth et al. have documented.

Howarth's most remarkable claim (317% increase in 6" days) is potentially misleading because it is a threshold statistic (see Section 8.4.2 above) and a ratio of small numbers over a short period. The result is not representative of *relative* extreme events for the whole region since the majority of stations never experienced a 6" total. Fig. 8.16 above determines the same number of events for each station (27 heaviest events) whose heaviest values ranged from 4.4" to 12.5" and their 27th heaviest values ranged from 3.3" to 5.0". This analysis thus allows each station to be equally represented. In

other words, if there is a region-wide increase in heavy events, it should be seen in the sum of all stations. Note too that the period of record here is 135 years vs. 36 years of Howarth et al. Except for three 5-year periods between 1995 and 2014 there is nothing statistically remarkable about the results in Fig. 8.4.7.

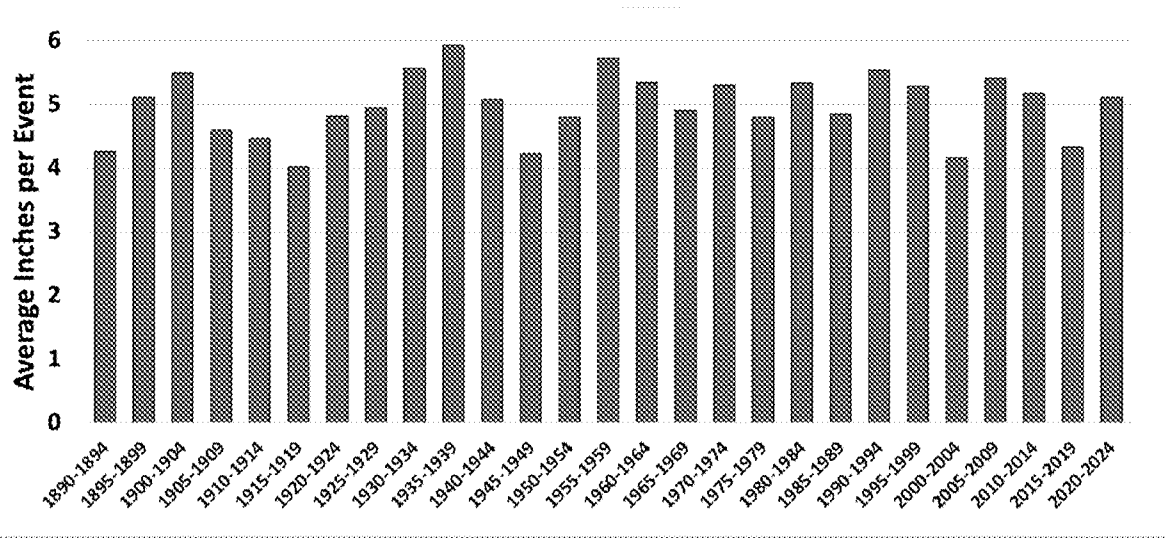


Figure 8.4.8. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

An interesting aspect of Northeast precipitation is that there has been no change in the amount of precipitation per heaviest event, as shown in Fig. 8.4.8. The trend is only $+0.02''/\text{decade}$. The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 8.4.6 and 8.4.7 suggest that though there was an uptick in the number of events during the period 1995 to 2014; the events, individually, are not becoming more intense.

Jong et al. (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded, "The autumn extreme precipitation trend over the Northeast US is primarily attributed to tropical cyclone-related events since the 1990s." The question then becomes, was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs? Jong et al. examined CMIP-6 model output which suggests that there will be fewer such systems in the 21st century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 8.17 where the amount-per-event has remained steady over the 135-year period.

For substantial urban areas there is some evidence to indicate the heaviest rainfall events may be redistributed due to the impact urban infrastructure has on the local weather (e.g., Pielke Sr. et al. 2011, Zhang et al. 2018, Yang et al. 2024). Yang et al. state, "Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with

dispersed development.” While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 8.17.

In summary, the evidence from the historical record of extreme precipitation events in the CONUS is generally not consistent from region to region so that inferences regarding trends and their projections are wrought with significant uncertainty. In most regions and perhaps all, it is our opinion that the very nature of the erratic and episodic character of extreme precipitation events renders the discovery of statistically significant changes, including a relationship to CO₂ concentrations, a result yet to be achieved (McKittrick and Christy 2019).

8.5 Summary

Based on the content provided in the document, here are the five most important takeaways:

1. Limited Detection of Anthropogenic Signals: The IPCC has asserted high confidence in detecting an anthropogenic signal in only 4 out of 34 weather impact categories, and medium confidence in 4 more. For the remaining 26 categories, no anthropogenic signal is claimed to be detected.
2. Slow Emergence of Trends: Even under the most extreme forcing scenario (RCP8.5), the IPCC expects very few anthropogenic trends to emerge within this century for most weather impacts.
3. Natural Variability Dominance: Natural variability continues to dominate patterns of extreme weather systems. Simple assertions of trend detection are often complicated by regional heterogeneity and trend reversals over time.
4. RCP8.5 Scenario Implausibility: The document notes that the RCP8.5 scenario is described as an implausible high-end storyline, not a "base case" or "business-as-usual" projection.
5. Conflicting Messages on Attribution: The document mentions that AR6 (IPCC Sixth Assessment Report) offers conflicting messages about the attribution of extreme weather to anthropogenic causes, highlighting the complexity and uncertainty in this area of climate science.

These takeaways emphasize the nuanced and complex nature of attributing extreme weather events to climate change, and the importance of considering natural variability and uncertainty in climate projections.

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From: Judith Curry <curry.judith@gmail.com>
Sent: Friday, May 9, 2025 2:52 PM
To: Ross McKittrick
Cc: Roy Spencer; John Christy; Steven Koonin; Travis Fisher
Subject: Re: Ch 8 Extreme weather

I don't like having pages of IPCC/NCA citations (IMO the key issue is a lot of uncertainty and disagreement, and the inconsistency between chapters 11 and 12 of AR6). If we do include a shortened version of this, i would focus only on AR6, either global or US region.

On Fri, May 9, 2025 at 11:45 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

In the attached Extreme Weather chapter draft I moved the IPCC/NCA excerpts back into the main body per the discussion here and renumbered all the sections and figures mutatis mutandis.

The AI summary is not bad but does need some work. Admittedly it's a lot of stuff to summarize, although the recurring theme is that trends aren't detectable and attribution to GHGs is currently not possible, in general.

On Thu, May 8, 2025 at 1:45 PM Roy Spencer <roywspencer@hotmail.com> wrote:

This way forward is fine with me.

-Roy

From: Judith Curry <curry.judith@gmail.com>

Sent: Thursday, May 8, 2025 12:43 PM

To: John Christy <climateman60@gmail.com>

Cc: Steven Koonin <steven.koonin@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>

Subject: Re: Ch 8 Extreme weather

I think starting with IPCC up front is very useful to provide a reference point, and discussing problems with NCA motivates the unpublished data analysis

On Thu, May 8, 2025 at 10:36 AM John Christy <climateman60@gmail.com> wrote:

Ultimately the order will likely not matter. We are somewhat conflicted. On one hand we show the Assessments are consistent with our conclusions about extreme weather, but on the other hand we find them (especially NCAs) deceptive in presenting the information that skews their results to lean toward alarmism. This is true of other chapters as well.

At the least we should mention this nuance perhaps up front.

John C.

Sent from my iPhone

On May 8, 2025, at 6:23 AM, Judith Curry <curry.judith@gmail.com> wrote:

I also agree with this organization, was thinking the same thing

On Thu, May 8, 2025 at 8:52 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Attached are my comments/edits on Chapter 8.

I'd like to make a strong pitch to reorder the text so that the survey of previous assessments comes first, then followed by the new work from John and Ross. There are several reasons for this that I can elaborate, but the most important is that the official assessments already make the case and, no offense guys, carry far more authority in the non-expert world.

SEK

PS Note for interest and amusement the AI-generated summary section.

From: Ross McKittrick <ross.mckittrick@gmail.com>

Sent: Tuesday, May 6, 2025 1:05 PM

To: John Christy <climateman60@gmail.com>

Cc: Judith Curry <curry.judith@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Steven Koonin <steven.koonin@googlemail.com>

Subject: Re: Ch 8 Extreme weather

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John C.

Sent from my iPhone

On May 6, 2025, at 4:14 AM, Ross McKittrick

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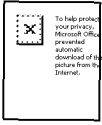
Ross

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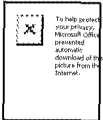
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Sent: Friday, May 9, 2025 3:09 PM
To: Ross McKittrick
Cc: Steven Koonin; John Christy; Roy W. Spencer; Travis Fisher
Subject: Re: Ch 8 Extreme weather

I agree we should have something up front, but not pages. Will propose something more specific

On Fri, May 9, 2025 at 12:06 PM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

My read of the discussion on May 8 was that Steve made a strong pitch to move the survey back up front and you and Roy concurred. I'll let you guys debate it.

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I have this para in the attribution chapter

The IPCC AR6 provides an ambiguous assessment of the role of global warming in the historical record of extreme weather and climate events. Chapter 11 of WG1 states (Seneviratne et al., 2021):

“Evidence of observed changes in extremes and their attribution to human influence (including greenhouse gas and aerosol emissions and land-use changes) has strengthened since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes (including dry/hot events and fire weather). Some recent hot extreme events would have been extremely unlikely to occur without human influence on the climate system.”

By contrast, Chapter 12 of WG1 (Table 12.12) paints a different picture – presumably, the expert judgment of different groups of authors for the two chapters came to different conclusions (Ranasinghe, 2021):

- High confidence in an increase in extreme heat events in tropical regions where observations allow trend estimation and in most regions in the mid-latitudes, medium confidence elsewhere
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I thought you said (May 8) you liked the suggestion to move them all back to the front.

On Fri, May 9, 2025 at 2:52 PM Judith Curry <curry.judith@gmail.com> wrote:

I don't like having pages of IPCC/NCA citations (IMO the key issue is a lot of uncertainty and disagreement, and the inconsistency between chapters 11 and 12 of AR6). If we do include a shortened version of this, i would focus only on AR6, either global or US region.

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In the attached Extreme Weather chapter draft I moved the IPCC/NCA excerpts back into the main body per the discussion here and renumbered all the sections and figures mutatis mutandis.

The AI summary is not bad but does need some work. Admittedly it's a lot of stuff to summarize, although the recurring theme is that trends aren't detectable and attribution to GHGs is currently not possible, in general.

On Thu, May 8, 2025 at 1:45 PM Roy Spencer <roywspencer@hotmail.com> wrote:

This way forward is fine with me.

-Roy

From: Judith Curry <curry.judith@gmail.com>

Sent: Thursday, May 8, 2025 12:43 PM

To: John Christy <climateman60@gmail.com>

Cc: Steven Koonin <steven.koonin@gmail.com>; Ross McKittrick <ross.mckitrick@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>

Subject: Re: Ch 8 Extreme weather

I think starting with IPCC up front is very useful to provide a reference point, and discussing problems with NCA motivates the unpublished data analysis

On Thu, May 8, 2025 at 10:36 AM John Christy <climateman60@gmail.com> wrote:

Ultimately the order will likely not matter. We are somewhat conflicted. On one hand we show the Assessments are consistent with our conclusions about extreme weather, but on the other hand we find them (especially NCAs) deceptive in presenting the information that skews their results to lean toward alarmism. This is true of other chapters as well.

At the least we should mention this nuance perhaps up front.

John C.

Sent from my iPhone

On May 8, 2025, at 6:23 AM, Judith Curry <curry.judith@gmail.com> wrote:

I also agree with this organization, was thinking the same thing

On Thu, May 8, 2025 at 8:52 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Attached are my comments/edits on Chapter 8.

I'd like to make a strong pitch to reorder the text so that the survey of previous assessments comes first, then followed by the new work from John and Ross. There are several reasons for this that I can elaborate, but the most important is that the official assessments already make the case and, no offense guys, carry far more authority in the non-expert world.

SEK

PS Note for interest and amusement the AI-generated summary section.

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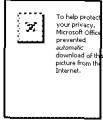
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From: Judith Curry <curry.judith@gmail.com>
Sent: Sunday, May 11, 2025 6:20 PM
To: Roy Spencer
Cc: Travis Fisher; Ross McKittrick; Steven Koonin; John Christy
Subject: Re: Ch 8 Extreme weather

Roy is correct. There is a total dearth of analysis on this topic, i am working with insurance companies to try to address this issue. But the summary statement from the AR6 saying "no signal" supports us not doing very much with this issue in this report (other than to mention the media hype against no evidence). Tornadoes are the only topic where there is any kind of analysis to draw from.

On Sun, May 11, 2025 at 12:59 PM Roy Spencer <roywspencer@hotmail.com> wrote:

Regarding tornadoes, strong to intense tornadoes in the US are down 50%, probably due to fewer Canadian cold air outbreaks over the western US in spring. Not sure whether anyone has added that yet. Severe thunderstorms require wind shear which is a function of cold and warm air masses, which is a mid-latitude issue. Instead, physicists and maths folks think it's thermodynamic buoyant energy that's important but if that was true the tropics would be full of severe thunderstorms.

-Roy

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Travis Fisher <travis.scott.fisher@gmail.com>
Date: 5/11/25 12:23 PM (GMT-06:00)
To: Judith Curry <curry.judith@gmail.com>
Cc: Ross McKittrick <ross.mckittrick@gmail.com>, Steven Koonin <steven.koonin@gmail.com>, John Christy <climateman60@gmail.com>, "Roy W. Spencer" <roywspencer@hotmail.com>
Subject: Re: Ch 8 Extreme weather

Will do. Apologies for the rambling email... I was trying to write with a kid on my lap. Just know I'm here to help!

On Sun, May 11, 2025 at 11:53 AM Judith Curry <curry.judith@gmail.com> wrote:

Travis, your comments on readability, gaps and red flag statements would be VERY helpful. The chapters all have a complete draft, but some are still in flux

On Sun, May 11, 2025 at 8:15 AM Travis Fisher <travis.scott.fisher@gmail.com> wrote:

As the non-expert member of the team, one of my contributions could be to provide input from the point of view of a reader who doesn't live and breathe these materials on a daily basis. With that in mind, I have a few observations that might help:

1) That said, I see no problem with adding more material. If the team is torn between the short version and the long version of any chapter, my preference is to leave more material and leave it to the reader whether to

dig in or skim. We don't exactly have a word or page limit on this. Also, the point about cherry-picking starting points for the data is very compelling to me. It reminds me of the first time I saw the chart of air pollution data with reference to EPA's formation. Of course the trend is sharply down for criteria pollutants after 1970, but it was on a similar trend *before* 1970 as well. Those types of data-based expositions can be very powerful in refuting common misunderstandings.

2) Some of the issues you all know incredibly well could use more elaboration for the uninitiated reader, especially when you agree fully with the consensus, IPCC, or NCA view. As one example, I was looking for more info on convective events in the extreme weather chapter. I know they are covered briefly, but my reaction as the non-expert was surprise at how little focus the consensus view gives them (and how lightly that fact was discussed in your chapter). I think we should emphasize the areas where, at least according to a typical reading of the news and popular narratives, climate change is blamed for things that aren't even on an upward trend. Thunderstorms and hailstorms are certainly part of that narrative. I'm less familiar with tornadoes entering the narrative, but it was news to me that there is essentially zero correlation with temperatures, and that type of information could be news to the typical reader as well. In other words, you could emphasize the areas where you all agree with IPCC/NCA/etc, which in turn would help anchor this report to the consensus view. That borders on a political or public affairs consideration, I know, so please feel free to ignore it completely.

3) I can see why the Secretary chose this team. You all are world-class experts. It's been a privilege to watch this report come together, and I'll do everything in my power to make it something you all can be proud of. If you want me to add comment bubbles to flag areas where the non-expert might trip up, I'd be happy to do that. Or if there's anything else I can do aside from the next glossary and the cover letter from the Secretary (and coordination with EPA), please let me know.

4) I took too long to hit send on this email, and I see a new one from Judy. +1 to Judy's point about leaving evaluations and judgments out of the body of the report. I may also try to flag areas where I see opinions or the inevitable pejorative. Personally, I had no idea how slick some of the NCA findings were in terms of narrowly defining the state of the climate to generate the appearance of a crisis, and I have become a new level of cynical after seeing it more clearly, thanks to you all. I'm excited to see the much-needed conversations this report will generate.

Best,
Travis

On Sun, May 11, 2025 at 11:06 AM Judith Curry <curry.judith@gmail.com> wrote:

Well the point of JC and RS analyses later in the chapter demonstrate the importance of looking back prior to 1950. And i think we should stick to conclusion statements in the SPM and Chapter summaries, rather than the text of the report that cites primary references (that looks like cherry picking). And AR6 is the main doc driving policy arguments; i don't think EPA lawyers are going to go back to AR5

On Sun, May 11, 2025 at 7:38 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

My concerns are that these excerpts leave out too much valuable material and that they lead with the AR6 cherry-picked 1950s as the starting point for trends. Both with respect to heatwaves and precip the only way to detect increases is to compare back to the 50s. If they include the 1930s or further back the heatwave picture falls apart, and as we show further in the chapter the precip picture falls apart either starting in the 70s or the 1800s. This selection puts us in a weak position where we will appear to be arguing against IPCC assessments using our own data, even though the more complete survey shows that our data aligns with what the assessments have been saying all along.

One reason to include material from the past assessment reports is that people have been hearing a narrative about extreme weather for 20+ years. A brief survey won't suffice to overcome the cognitive dissonance we're up against in this chapter. The comprehensive survey of IPCC and NCA material is the only way to overcome it. If we only show the AR6 they might think that's somehow new whereas prior reports said something else. I want to show convincingly that the message today is about the same as it's always been.

For those of us who know what the IPCC says and has said in the past it might seem tedious to quote it at such length. But I've presented to enough undergrad classes and public audiences to know that people don't find these quotes boring, they find them incredible. If it's a question of chapter order I don't mind if there's a brief preface then the whole collection goes into the chapter appendix, but I see no benefit to omitting the material and considerable gain from including it. And I still think the best option is to lead with it.

What say others?

On Sat, May 10, 2025 at 5:55 PM Judith Curry <curry.judith@gmail.com> wrote:

See attached for my smash down of section 8.2 (13 down to 2 pages). I included on detection statements (no attribution or projections); focused on AR6 and included some statements from NCA17 and SREX that provided additional detail. I focused on summary statements from the SPM and chapter summaries (without citations of individual papers)

Let me know what you think, and whether you prefer it up front or at the end (maybe an appendix)

On Sat, May 10, 2025 at 11:52 AM Steven Koonin <steven.koonin@gmail.com> wrote:

I like John's suggestion.

Steven E. Koonin

On May 10, 2025, at 14:36, John Christy <climateman60@gmail.com> wrote:

Judy

Would this work. Put the IPCC/NCA quotes in bold up front with a little introductory remark then add "full statements in context in appendix"?

John C.

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On May 10, 2025, at 5:49 AM, Judith Curry <curry.judith@gmail.com> wrote:

I'm working on CH 8 Extreme Weather front end today, more soon

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Yes! In the exec summary and the chapter preface we must repeat something like “Contrary to popular perception...”

Steven E. Koonin

On May 10, 2025, at 11:19, Ross McKittrick

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This just appeared in the Daily Mail

<https://www.dailymail.co.uk/sciencetech/article-14686539/climate-change-affect-YOU-heatwaves-floods.html>

The extreme weather alarmism angle has been non-stop for years. People are saturated with the message that climate change = extreme weather and all scientists say it's bad and getting worse due to GHGs. It will take a lot of hammering on the theme to convince people how much they've been misled. So I don't mind if the first 15 pages of this chapter consists of mind-numbing repetition of the message that scientists don't say this and have never said it. At this point I want to hold the readers' faces in it until their limbs stop twitching and then they'll be receptive to the rest of the material.

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On Fri, May 9, 2025 at 11:45 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

In the attached Extreme Weather chapter draft I moved the IPCC/NCA excerpts back into the main body per the discussion here and renumbered all the sections and figures mutatis mutandis.

The AI summary is not bad but does need some work. Admittedly it's a lot of stuff to summarize, although the recurring theme is that trends aren't detectable and attribution to GHGs is currently not possible, in general.

On Thu, May 8, 2025 at 1:45 PM Roy Spencer <roywspencer@hotmail.com> wrote:

This way forward is fine with me.

-Roy

From: Judith Curry <curry.judith@gmail.com>

Sent: Thursday, May 8, 2025 12:43 PM

To: John Christy <climateman60@gmail.com>

Cc: Steven Koonin <steven.koonin@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>

Subject: Re: Ch 8 Extreme weather

I think starting with IPCC up front is very useful to provide a reference point, and discussing problems with NCA motivates the unpublished data analysis

On Thu, May 8, 2025 at 10:36 AM John Christy <climateman60@gmail.com> wrote:

Ultimately the order will likely not matter. We are somewhat conflicted. On one hand we show the Assessments are consistent with our conclusions about extreme weather, but on the other hand we find them (especially NCAs) deceptive in presenting the information that skews their results to lean toward alarmism. This is true of other chapters as well.

At the least we should mention this nuance perhaps up front.

John C.

Sent from my iPhone

On May 8, 2025, at 6:23 AM, Judith Curry <curry.judith@gmail.com> wrote:

I also agree with this organization, was thinking the same thing

On Thu, May 8, 2025 at 8:52 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Attached are my comments/edits on Chapter 8.

I'd like to make a strong pitch to reorder the text so that the survey of previous assessments comes first, then followed by the new work from John and Ross. There are several reasons for this that I can elaborate, but the most important is that the official assessments already make the case and, no offense guys, carry far more authority in the non-expert world.

SEK

PS Note for interest and amusement the AI-generated summary section.

From: Ross McKittrick
<ross.mckittrick@gmail.com>
Sent: Tuesday, May 6, 2025 1:05 PM
To: John Christy
<climateman60@gmail.com>
Cc: Judith Curry
<curry.judith@gmail.com>; Roy W. Spencer

<roywspencer@hotmail.com>; Travis
Fisher
<travis.scott.fisher@gmail.com>;
Steven Koonin
<steven.koonin@googlemail.com>
Subject: Re: Ch 8 Extreme weather

Here's another edition of Ch 8 on extremes taking Judy's and John's points into account. The IPCC/NCA review is ported to an Appendix. I added a paragraph about LTP to the intro. I've incorporated the NE data. The bulk of the chapter is John's US temperature and precip data analysis with some additional material on wildfires, drought and TCs. For the US temperature extremes I moved the range figure to come just after the hot/cold extremes count because I think they both make a coherent point namely that the US becoming less extreme because heat events are rising more slowly than cold events are warming. There will still need to be an overall chapter summary but I'm going to move on to other chapters now. I'll put this in the Dropbox.

On Tue, May 6, 2025 at 12:12 PM
John Christy
<climateman60@gmail.com>
wrote:

All

We can fill in without much trouble the change, or lack thereof, of “high impact” weather events (mainly wind and flooding

like hurricanes, tornadoes etc) in the CONUS Extreme chapter. The temp and precip metrics are important because they are just long enough to essentially tell us Mother Nature has a mind of her own.

1. I'll look at Ross's version of 8 soon, but my hope was that Ross would translate the statistical remarks into the correct language(eg are their more precise words that chaotic, episodic, stochastic, etc).

2. We have analyses of the CONUS with more complete datasets than the NCA used (recall NCA analyses depended essentially on a small group at NCEI using datasets that (a) were not very consistent in time, (b) could promote alarm and (c) already easy for them to get to. Our datasets have literally hundreds of thousands of manually keyed-in observations for temporal consistency. In other words, this lets people know we can address these issues from soup to nuts - we're not armchair climate scientists ... we can reproduce what they did, but make the analysis more comprehensive to address the questions.

John C.

Sent from my iPhone

On May 6, 2025, at
4:14 AM, Ross
McKitrick

<ross.mckitrick@gmail.com> wrote:

Just read your attribution chapter. I hadn't picked up on the gap between IPCC Ch 11 vs Ch 12 language but i see your point that rather than promoting one set of attribution findings we should explain that even within the same AR different authors assessed things differently. One option is to leave Ch 6 where it is but reverse the order of Ch 7 and 8 while retitling the latter as you suggest. That way, having established the extreme weather types for which there are no detectable trends it will more naturally follow that they won't be discussed in the attribution chapter.

On Tue, May 6,
2025 at 9:45 AM
Judith Curry
<curry.judith@gmail.com>
curry.judith@gmail.com> wrote:

Ok, but the
summary table
(12.12 from AR6)
is inconsistent
with conclusions
in AR6 ch 11 (I
point this out in
section 6.4 of my
attribution
chapter).

In my mind, the
main point is
disagreement and
ambiguity I
would suggest
chapter 8 going
before chapter 6,
retitling it as US
Weather and
Climate
Extremes, and
make it more of a
data chapter, not
an attribution
chapter (I would
put table 12.12 in
the attribution
chapter if you
want to include
the actual table)

On Tue, May 6,
2025 at 6:39 AM
Ross McKittrick
<ross.mckittrick@gmail.com>
ross.mckittrick@gmail.com>
wrote:

I like john's material too which is why I included it and am working on the extended regional analyses. But on this topic people are heavily primed to believe that extreme weather of all kinds is getting worse due to climate change. The assertion shows up everywhere climate change is discussed including in academic papers. I think it is very valuable to show people that neither the IPCC nor the NCA support such this view. We should at least lead off with the summary table. The library of quotes can go to an appendix but I have found in my public speaking that they have considerable persuasive force for most people. We also need to address floods, droughts, hurricane landfalls, tornadoes etc. I don't see any

reason to delete
all that material.

On Tue, May 6,
2025 at 9:22 AM
Judith Curry
<curry.judith@gmail.com>
wrote:

I actually liked
John's
chapter. I
would have
retitled it "US
temperature and
rainfall
extremes"

I think this is
more relevant
than a complete
rehash of
everything the
last 3 IPCC
reports have
stated for every
conceivable
severe weather
event.

John's version
meshes very
well with my
version of
chapter 6. Read
especially
section 6.4 of
my chapter. I
note a
discrepancy
between
chapters 11 and
12 in terms of
detecting and
attributing
extreme

events. This is the main point in my opinion, there is ambiguity in all this. Lets focus on pointing out the problems/challenges, and topics that are particularly relevant for the US

On Mon, May 5, 2025 at 7:47 PM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

I have wrangled the extreme weather chapter into something I hope flows better and is more readable. I adopted Judy's editorial changes and then the new changes I made are in red. I added some new Figures showing results on PC and SE data and will add the

NE chart when
I get the data. I
also made
some labeling
suggestions
including for
the 3 rainfall
charts that are
hard to
understand.
Section
summaries and
an overall
summary are
still needed.

Ross

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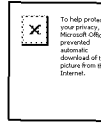
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<http://www.cfanclimate.net>

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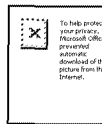
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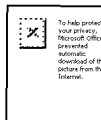
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<http://www.cfanclimate.net>

From: John Christy <climateman60@gmail.com>
Sent: Monday, May 5, 2025 10:54 PM
To: Ross McKittrick
Cc: Judith Curry; Roy W. Spencer; Travis Fisher; Steven Koonin
Subject: Re: Ch 8 Extreme weather
Attachments: [8.2, 8.4]_Extremes_T_P_5May[JRC].docx; Untitled attachment 00722.htm

Ross

I'm somewhere over the Pacific heading to Honolulu. I just finished this rewrite, but will see what you have. It will be interesting to compare.

I haven't looked at floods. I really don't want to make my self smart on blizzards, but I do have the most extensive seasonal snowfall dataset for the Cascades and Sierras.

John C.

John Christy
Director, Earth System Science Center
Professor, Atmos and Earth Science
Alabama State Climatologist
The University of Alabama in Huntsville
climateman60@gmail.com

8 Introduction

Weather extremes, usually related to temperature and/or precipitation, often disrupt infrastructure and therefore human health and thriveability. Indeed, the ability of any surface-dwelling species to live productively is somewhat constrained by these extremes which in essence create the bounding limits for survival. The issue here is whether these extremes, and their attendant potential danger, may be changing in response to increases in infrared-absorbing greenhouse gases (*GHGs*) (e.g., IPCC AR6 Seneviratne et al. 2021).

Unfortunately, the sample of time from which we are able to quantitatively analyze variations in extreme events is quite brief, around 130 years. This period certainly does not begin to contain all of the extreme events that the climate system is able to create naturally. Over geologic time the climate system has generated an (essentially) infinite variety of patterns and extremes which humans have never observed, and thus do not enter our databases from which extreme statistics are determined [see 6.4 and 8.4 below]. Thus, assuming that a new climate pattern or event in our lifetime is somehow the result of enhanced GHG concentrations requires the assumption that natural variations are insignificant. This is especially true for precipitation events. With this caveat in mind we examine the evidence for changes in weather and climate extremes.

Section 8.2. Extremes in daily temperatures in the Conterminous US (CONUS)

Daily maximum temperatures in the warm season (TMax, May-Sep) and daily minimum temperatures in the cold season (TMin, Dec-Mar) are available, beginning in Dec 1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (Quinlan et al. 1987, Karl et al. 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although errors certainly reside

in the dataset, with over 1,000 stations any underlying signal we discover can be characterized by relatively high confidence.

8.2.1 Daily record extremes in TMax and TMin

Has the occurrence of daily record high or low temperatures changed since Dec 1898? Each warm-season has 153 days (1 May to 30 Sep) and each cold-season has 122 days (1 Dec to 31 Mar). For each of these days and each of the stations we calculated the year in which the record highest (lowest) temperature occurred. (Binning of the results to bring out the longer-term variations will be performed in 6-year intervals as 126 is evenly-divisible by 6.) With 126 years of observations, we would expect, on average, that a station would experience an average each year of 1.21 records for TMax and 0.96 records for TMin. Figure 8.2a indicates the distribution in time of the occurrence of these extreme events.

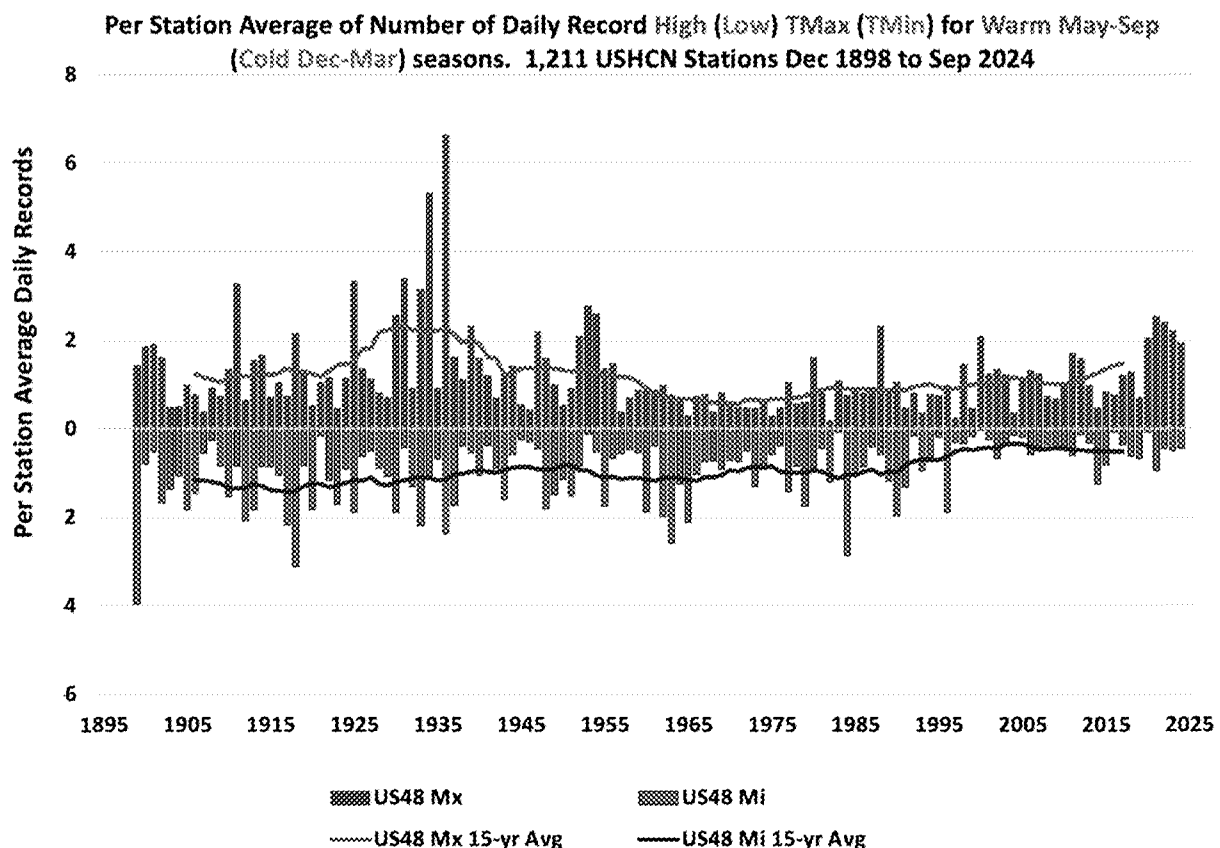


Figure 8.2a. Per station average of number of daily record High (red) and Low (blue) for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average.

Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92% of observations in the 126-year period since Dec 1898.

The results indicate a common feature in many metrics of warm-season extremes in the CONUS - the exceptional heat of the 1920s and especially the 1930s peaking in 1936. On a per-station average, 60% of the TMax records and 59% of the TMin records occurred in the first half of the period (1899-1961).

The Valentine's Day Arctic outbreak in Feb 1899 stands as the most extensive cold extreme experienced in the CONUS in the instrumental era. The frequency of cold records has declined, especially over the past quarter of the period in which only 13% of the extreme cold events were measured. In contrast, 25% of the extreme TMax records were achieved in the last quarter in accordance with statistical expectations. These general features have been noted in past assessments (IPCC AR5, IPCC AR6, NCA4, NCA5).

8.2.2 Heat Thresholds

Under the heading of "The Risk of Temperature Extremes is Changing", the most recent US National Climate Assessment report (NCA5) notes the increase in a threshold metric of number of days at or above 95°F, stating,

"The western US has been particularly affected by extreme heat since the 1980s ..., experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021."

Are the occurrences of 95°F days changing? As a non-parametric statistical variable, a threshold statistic can be misleading. A region with many stations which have near 95°F TMax average temperatures in the summer might see large swings in the metric when only small changes in average temperature occur. Elsewhere with stations that either rarely or virtually always achieve 95°F TMax temperatures, a small change will not impact the results much at all. In the past 126 years, the average CONUS station experienced 129 days per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, one needs to view such threshold analyses with caution.

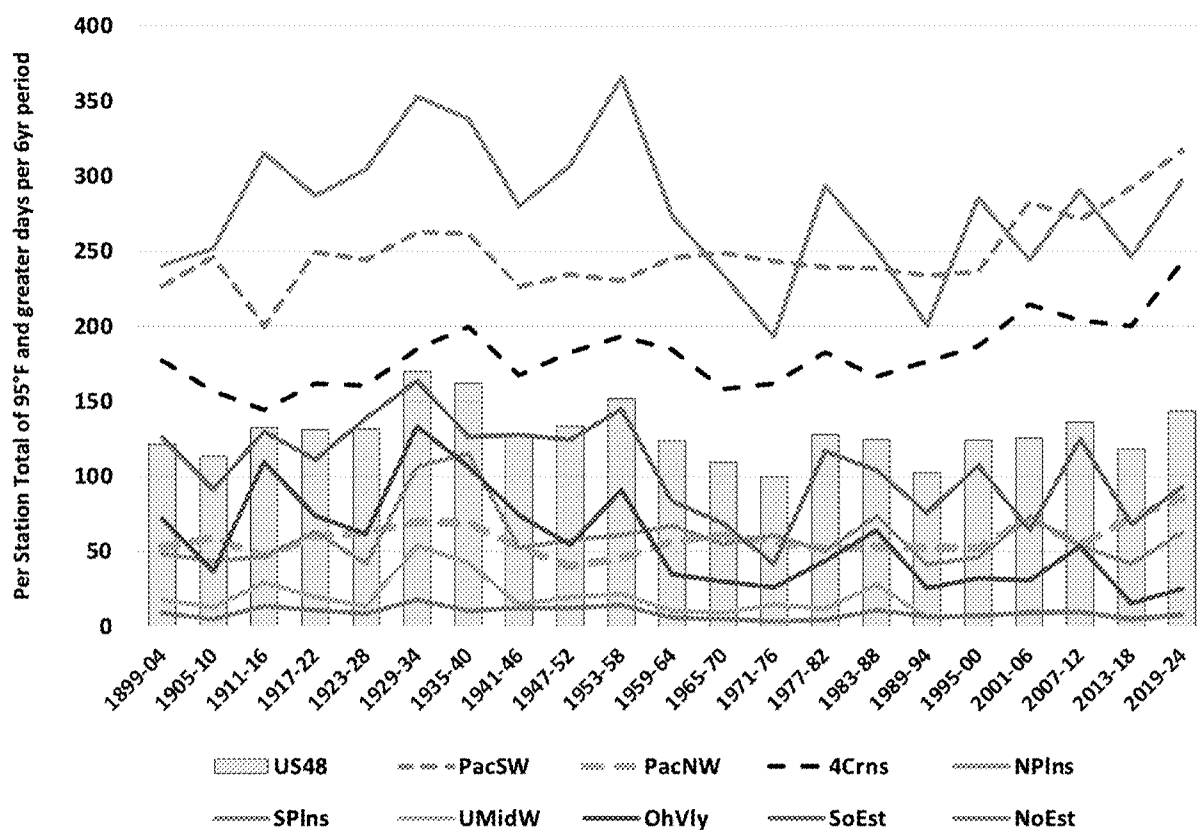


Figure 8.2b. Per station average of total number of days > 94°F per 6-yr period. Dashed lines indicate regions with positive trends.

In Fig. 8.2b we see that only three of the nine regions, all in the West (dashed lines), have experienced positive trends for TMax 95°F or hotter. The entire CONUS and the other six regions have experienced declines.

The Pacific NW heatwave of 2021 is referenced as supportive information for the NCA5 claim, an event examined in section 6.4. The evidence indicates it was a “black swan” event, i.e. unprecedented in the existing record, suggesting it is not indicative of a pattern of increasing extreme heat. The tropospheric temperature anomaly over the Pacific NW was +11.0 C, the most extreme NH grid point summer anomaly in the 46 years of 5-day readings from over 4 million grids - even though the global anomaly was virtually zero (+0.03 C, Mass et al. 2024).

The heading “The Risk of Temperature Extremes is Changing” suggests positive trends are now being observed in threshold temperatures on a widespread basis, but that is not evidenced in the combined CONUS results of the figures above.

8.2.3 Heatwaves

Of more impact than a single daily record is the phenomena of heatwaves, or consecutive days which exceed an extreme threshold. For this study, the metric will be the number of “Heatwave Days” defined as the sum of all days in May-Sep each year which exceed the 90th percentile on consecutive days of at least seven days in length (NCA5 used 6-day periods, with almost identical results as below).

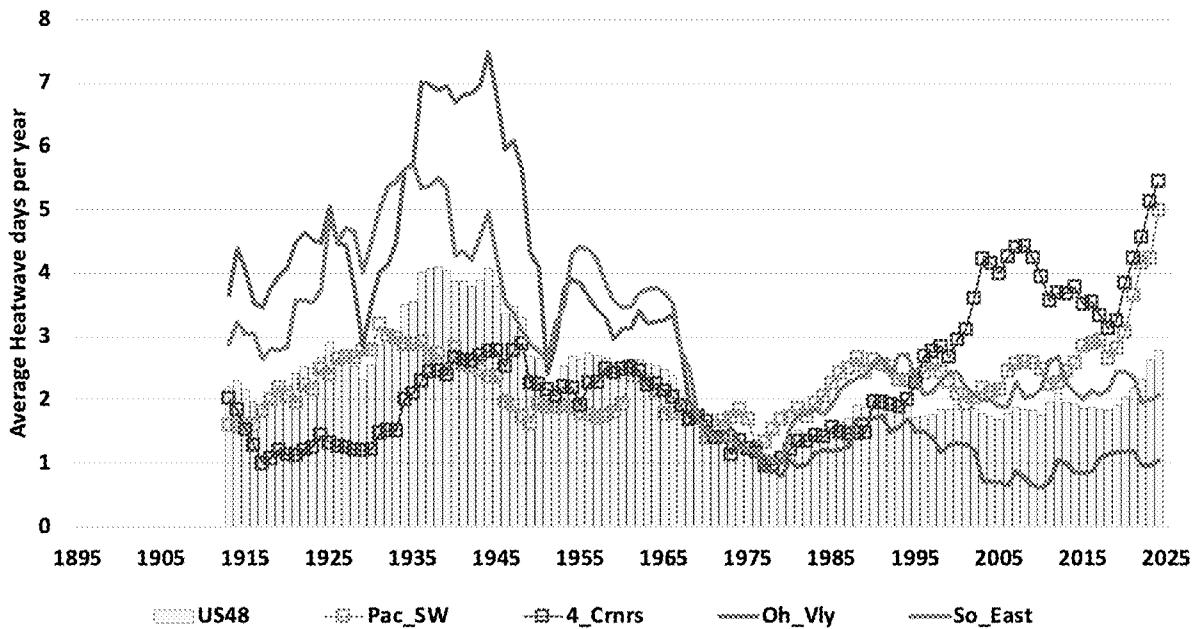


Figure 8.2c 15-year trailing average of number of heatwave days per year per station in the CONUS (bars) and four regions: Pac_SW (orange squares, CA, NV), 4_Crnrs (red squares, AZ,NM,UT,CO), Oh_Vly (blue, MO, IL, KY, TN, IN, OH, WV) and So_East (green, MS, AL, GA, FL, SC, NC, VA).

Figure 8.2c indicates, again, the excessive heat of the first half of the 20th century, primarily in the eastern two-thirds of the nation, as seen in the sub-regional values for the Ohio Valley and the Southeast as examples. The West has seen a recent increase of heatwave days and the two sub-regions with the highest number are shown, the Pacific Southwest and the Four-Corners (NCA5).

Of interest here is the regional variation of this metric. The four northern regions (Pacific NW, Northern Plains, Upper Midwest, and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains, Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

Overall, the complete time series indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20th century, but in the 21st century the patterns have favored heatwaves in the West.

Regarding a different heatwave metric, NCA5 directs readers to the website

<https://www.globalchange.gov/indicators/heat-waves> (USGCRP 2023) to view the number of urban heatwaves by decade from the 1960s. The figure reveals a monotonic increase in each decade from 2 occurrences per year in the 1960s to 6 in the 2020s. The definition of a heatwave is unusual but practical from a human discomfort perspective - a period of at least 2 consecutive days when the apparent minimum temperature (combination of temperature and humidity) exceeds the 85th percentile. Note too, the dataset is limited to the 50 largest cities in the US.

These increasing values since 1960 presented in USGCRP (2023) are entirely reasonable, but for at least two reasons unrelated to GHG emissions. Urbanization in these cities is a major factor in the rise of TMin relative to co-located TMax and relative to TMin at rural stations. Also, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. This does not dismiss the real rise in nighttime temperatures in major US cities and the societal impacts associated with these changes. However, we note for a variety of reasons, that summer TMax (especially in rural areas) serves as better response variable for detecting potential changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs – our concern in this document (Christy et al. 2009). For the CONUS as a whole, the evidence in this section suggests GHG emissions have had little-to-no effect on heatwaves in the CONUS.

8.2.4 Range of extremes

In the metrics above, a common feature emerges in which the range of CONUS temperature extremes has experienced a decline in the last 126 years.

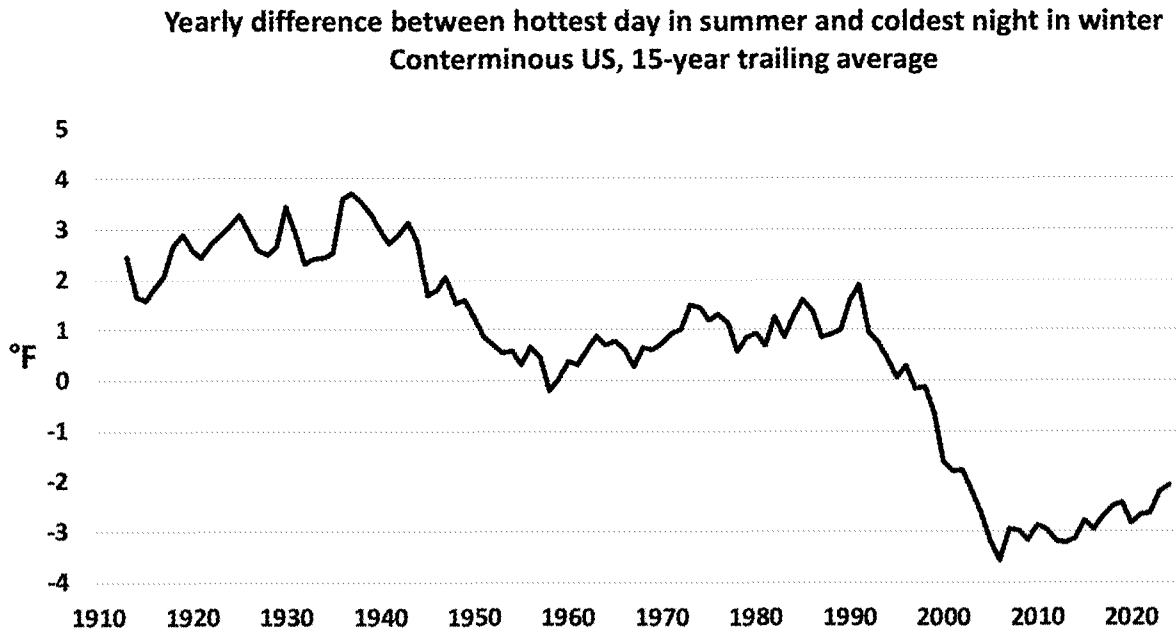


Figure 8.2d. 15-year trailing average of the difference each year of each station's hottest warm-season TMax and coldest cold-season TMin relative to the long-term average.

Figure 8.2d shows that the average difference for each station between the hottest summer TMax and coldest winter TMin has declined about 5°F in the past 126 years. The decline is due mostly to the warming of winter TMin, but a decline in the magnitude of summer TMax is also a factor. The rise in TMin has been strongly related to the growing presence of manufactured surfaces (development around most stations) disrupting the natural heat fluxes and thus near-surface air temperature over the last 100+ years (Spencer et al. 2025).

In summary, the information from these analyses (and other assessments) indicates that any change in metrics of daily temperature extremes in the CONUS is difficult to ascribe to enhanced GHG concentrations. This is especially so since many of the TMax-based time series reveal negative trends.

8.4 Extremes in Precipitation

Due to its stochastic and episodic character, precipitation requires careful statistical treatment to understand variability over long time periods. Of concern in this report is the reasonable assumption that warmer air has a greater capacity to hold moisture and thus if the atmosphere warms (a GHG response), which could lead to extreme events of greater frequency and/or magnitude (NCA5).

The two recent US National Climate Assessments (NCA4, NCA5) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of the CONUS and greatest in the Northeast (when starting in either 1901 or 1958). Interestingly, the regional variations indicate that the largest increases in extreme events are in the Northeast and least in the West, which is counter to the changes in temperature extremes shown above.

McKittrick and Christy 2019 examined long-term and consistent station observations of daily precipitation to test some of these NCA5 claims for the Southeast and West Coast. In neither case when the time series were extended back in time (as far as 1872 in some cases) or when starting later (1978) were the trends significant. We update these findings with 29 stations on the Pacific Coast (1893ff from San Diego CA to Blaine WA), 24 stations in the humid Southeast (1872ff from Austin TX to Washington DC), and 21 stations in the Northeast (1888ff from Buffalo NY to Portland ME – the subregion where trends are greatest).

The Pacific Coast receives considerable, often extreme, amounts of precipitation from Atmospheric River (AR) events which usually last more than a day or two (e.g., Gershunov et al. 2017, Pan et al. 2024). To examine the variability in time of the heaviest events, Fig. 8.4a answers the question, “When have the heaviest 5-day events occurred from 1895 to 2024 (130 years) along the Pacific Coast of the CONUS?” Each of the 29 stations contributes 26 events (a

nominal 1-in-5 yr extreme event). The widespread deluges associated with the massive 1997-98 El Niño event are readily apparent in Fig. 8.4a. While erratic, as is typical of these types of precipitation metrics, there is no indication of a tendency of change over time.

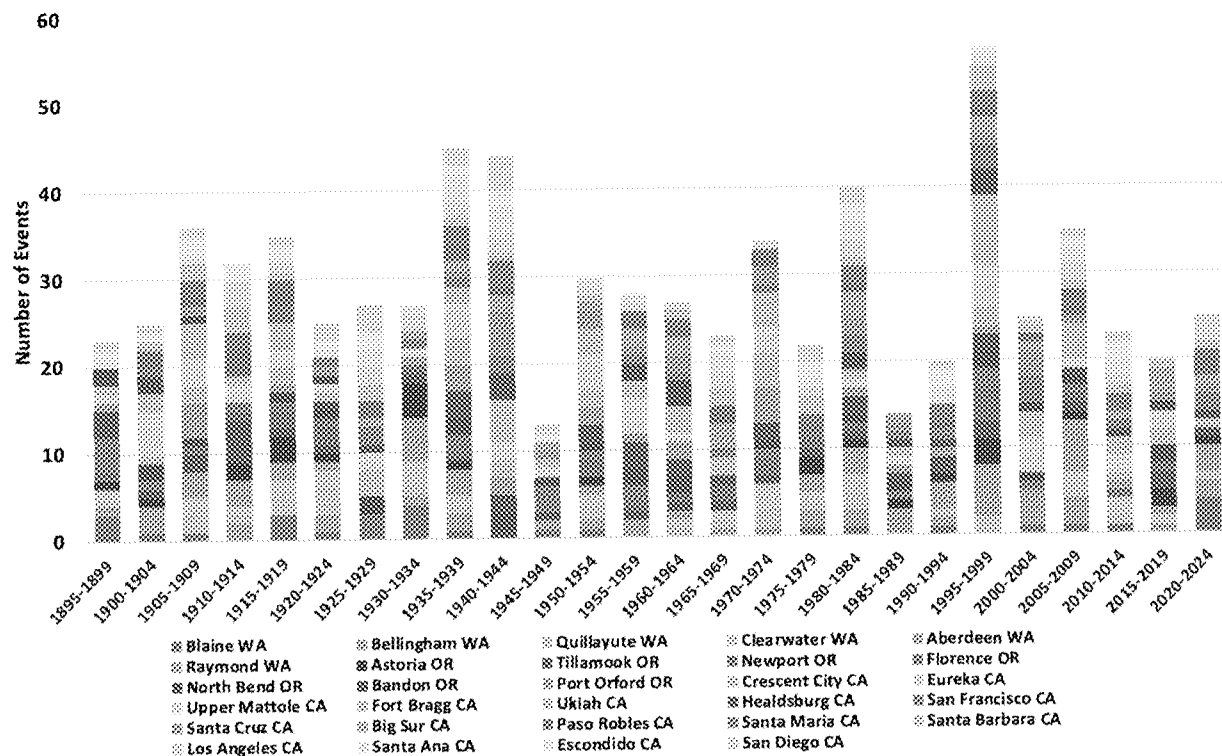


Figure 8.4a. The time distribution of the heaviest 5-day totals for Pacific Coast stations (i.e., nominal 1-in-5 yr event). Each color represents one station, each contributing 26 events ($\approx 130\text{yr}/5$) to the entire result. Each column represents the total number of extreme events occurring in the identified interval as a sum of all station contributions.

Sidebar.

An example of the limitation of using a small sample to characterize natural variability in order to assess potentially changing extreme events: San Francisco.

Figure 8.4a is calculated from 29 stations with complete daily observations from 1895 to 2024 or 130 years. Daily precipitation for San Francisco has been

observed since 1850, and thus provides information on earlier events, especially of the ArkStorm of 1861-62, where so much precipitation fell that California's San Joaquin and Sacramento Valleys were under water for weeks. This resulted in considerable devastation (Brewer 1930, Null and Hulbert 2007).

Table 8.4a lists the extreme events based on Fig 8.4a (130 years) for San Francisco in comparison with the record beginning in 1850 (175 years). As can be seen there were extreme events of even greater magnitude in these additional 45 years.

Table 8.4a List of most extreme precipitation events for two periods, 1850-2024 and 1895-2024.

	1850- 2024			1895- 2024		Rank of 130-yr Extreme	Percentage greater
Duration	Extreme Amount Inches	Year		Extreme Amount Inches	Year	130-yr Extreme ranked vs. 175-yr Extremes	175-yr Extreme vs. 130-yr Extreme
3-day	8.85	1867		6.94	2023	3	+27.5
5-day	9.80	1867		8.55	2023	3	+14.7
14-day	19.05	1862		12.62	2023	4	+51.0
30-day	28.25	1862		18.93	1998	2	+49.2

However, the characterization of the range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter et al. 2011 discovered that in the past 1,800 years at least six megastorms that were more intense than the devastating 1861-62 ArkStorm struck the region. Thus, such

extreme events have impacted the region about every 300 years, though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability. Accurate representation of the full range of natural variability is necessary for any attribution analyses (section 6.4). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time-sample of 130 years provides an underestimation of the extreme value by up to 50% determined when adding only 45 more years of observations. With millennial-scale paleoclimate evidence, an even greater underestimation would be forthcoming.

Moving to the humid Southeast Fig 8.4b indicates the temporal pattern of 5-day totals of the 1-in-5yr heavy events is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA4 and NCA5 of a tendency for an increasing frequency of heavy events, due to a temporal clustering of tropical storms, from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events.

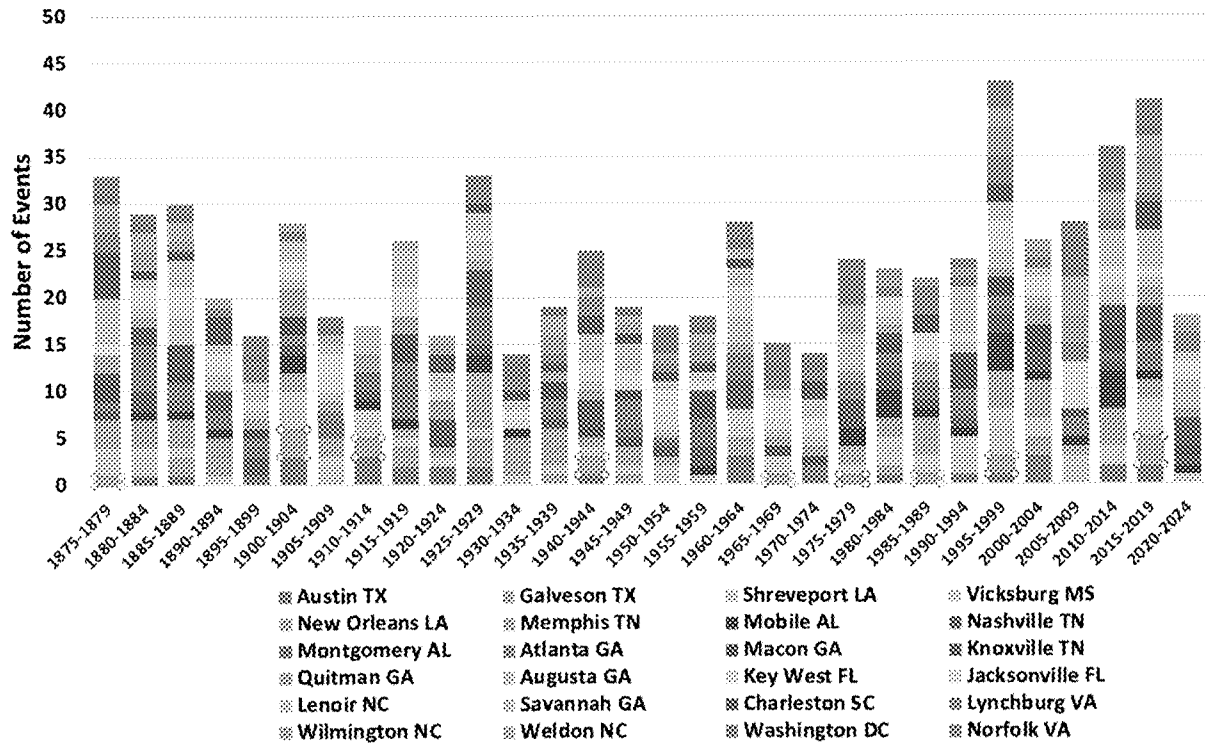


Figure 8.4b. As above but for the 30 heaviest 1-in-5yr events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1875-2024.

In Fig. 8.4c is displayed the 27 (1-in-5yr) heaviest 3-day events for the last 135 years in 21 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest variations in time, and shall look more closely at this region because this is the source of the greatest increases in heavy events. In this region, 72% of the events occur during June to October and are dominated by tropical incursions of hurricanes, tropical storms, depressions and tropical systems that transition to an extratropical character.

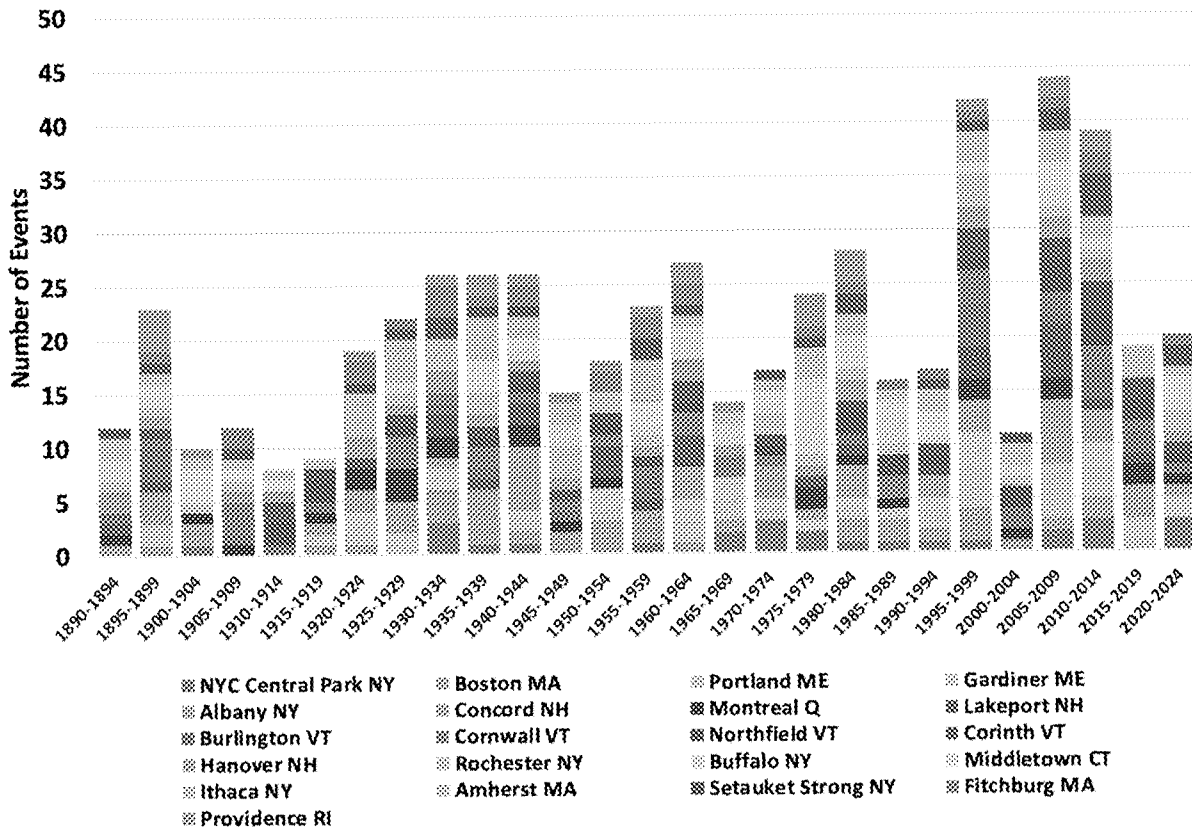


Figure 8.4c. As in Fig. 8.4a but for the heaviest 3-day precipitation events for 21 stations from NY to ME, including Montreal. Each station contributes its 27 (=135/5) heaviest 3-day events.

Howarth et al. 2019 report differences in the Northeast between two 18-year periods: 1979-96 and 1997-2014 (a similar region as in Fig. 8.4c but that includes PA and NJ) of various precipitation extremes. One metric which indicated a dramatic increase (317%) was found for 24-hr events > 6 inches. This high increase is due to the very small numbers of such events of which there were only 6 in the first period and 25 in the second out of 58 stations. Most of the stations did not record such an event suggesting these erratic, episodic events over brief, 18-yr periods, need scrutiny by additional statistical methods.

Using the information in Fig. 8.4c over the same years as Howarth et al. we find an increase of the frequency of heavy events between the two periods of 51%. One can see in Fig. 8.4c that it

was unfortunate that Howarth et al. ended in 2014 prior to a return to the long-term average of such events.

The method of Howarth et al. was to analyze single day (24-hr) totals which is questionable because extreme events are often spread across the time-of-observation boundaries. Stations measuring at 0700 LT versus those at Midnight will have differing results and which would then have major impacts on counting rare events. We use the 3-day totals in Fig. 8.4c to be sure to capture the extent of these short events. In any case, we can confirm that the period 1997 to 2014 provided a cluster of heavier events as Howarth et al. have documented.

Howarth's most remarkable claim (317% increase in 6" days) is potentially misleading because it is a threshold statistic (see above under Heat Threshold) and a ratio of small numbers over a short period. The result is not representative of *relative* extreme events for the whole region since the majority of stations never experienced a 6" total. Fig. 8.4c above determines the same number of events for each station (27 heaviest events) whose heaviest events ranged from 4.4" to 12.5" and their 27th heaviest events ranged from 3.3" to 5.0". This analysis thus allows each station is equally represented. In other words, if there is a region-wide increase in heavy events, it should be seen in the sum of all stations. Note too that the period of record here is 135 years vs. 36 years of Howarth et al. Except for three 5-year periods between 1995 and 2014 there is nothing statistically remarkable about the results in Fig. 8.4c.

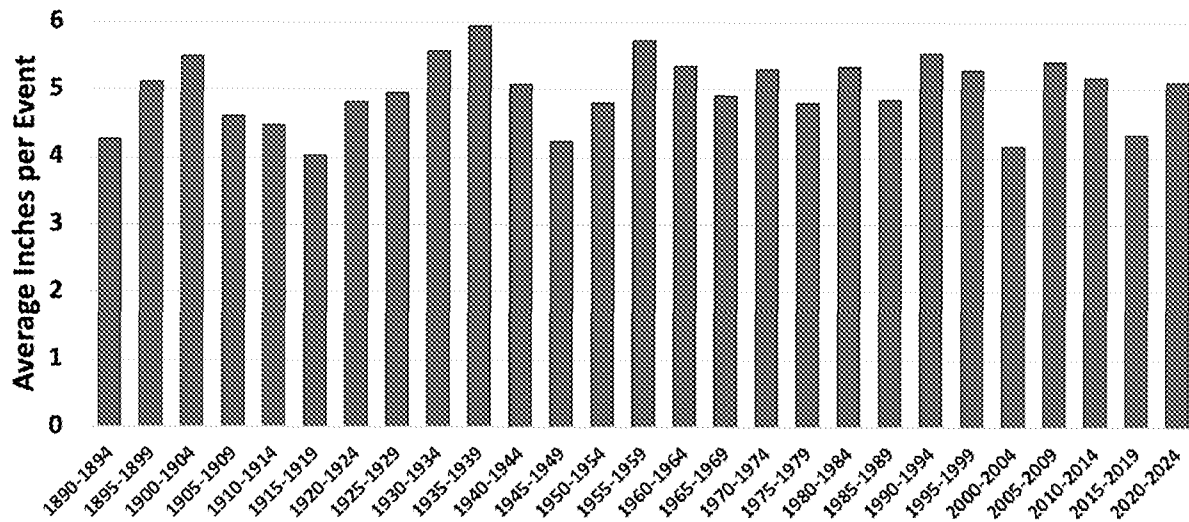


Figure 8.4d. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

An interesting aspect of Northeast precipitation is that there has been no change in the amount of precipitation per heaviest event as seen in Fig. 8.4d (a minuscule trend of $+0.02''/\text{decade}$). The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 8.4c,d suggest that though there was an uptick in the number of events during the period 1995 to 2014; the events, individually, are not becoming more intense.

Jong et al. 2024 document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded, “The autumn extreme precipitation trend over the Northeast US is primarily attributed to tropical cyclone-related events since the 1990s.” The question then becomes, was the temporal clustering of tropical systems in the Northeast during 1997-2014, a response to increasing GHGs? Jong et al. examined CMIP-6 model output which suggests that there will be fewer such systems in the 21st century but that the intensity of the rainfall events might increase. This latter hypothesis is not consistent with Fig. 8.4d where the amount-per-event has remained steady over the 135-year period.

For substantial urban areas there is some evidence to indicate the heaviest rainfall events may be redistributed due to the impact urban infrastructure has on the local weather (e.g., Pielke Sr. et al. 2011, Zhang et al. 2018, Yang et al. 2024). Yang et al. state, “Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with dispersed development.” While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 8.4d.

In summary, the evidence from the historical record of extreme precipitation events in the CONUS is generally not consistent from region to region so that inferences regarding trends and their projections are wrought with significant uncertainty. In most regions and perhaps all, it is our opinion that the very nature of the erratic and episodic character of extreme precipitation events renders the discovery of statistically significant changes, including a relationship to CO₂ concentrations, a result yet to be achieved (McKittrick and Christy 2019).

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On May 5, 2025, at 9:47 PM, Ross McKittrick <ross.mckitrick@gmail.com> wrote:

I have wrangled the extreme weather chapter into something I hope flows better and is more readable. I adopted Judy's editorial changes and then the new changes I made are in red. I added some new Figures showing results on PC and SE data and will add the NE chart when I get the data. I also made some labeling suggestions including for the 3 rainfall charts that are hard to understand. Section summaries and an overall summary are still needed.

Ross

<8 Extreme weather.RM.May05.docx>

From: Judith Curry [curry.judith@gmail.com]
Sent: 5/14/2025 6:19:46 PM
To: John Christy [climateman60@gmail.com]
CC: Ross McKittrick [ross.mckitrick@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]; Steven Koonin [steven.koonin@gmail.com]
Subject: Re: Ch 12 mortality

The IPCC quotes are in Ch 7. I think one of the conclusions for Ch 7 should be regional variability of trends in extremes

On Wed, May 14, 2025 at 11:17 AM John Christy <climateman60@gmail.com> wrote:
Ross:

This first paragraph seems at odds with Chapter 7 where changes in extremes were not found. Is this a claim drawn from the IPCC docs? If so, it needs a citation.

John C.

12 Mortality from temperature extremes

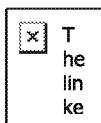
12.1 Heat and cold risks

Changes in temperature extremes are among the most certain impacts expected in a warming world. Extreme heat events are likely to become more frequent while extreme cold events become less frequent. This pattern is evident in the historical period (Chapter 7) and is expected to continue with further warming.

On Wed, May 14, 2025 at 1:12 PM Judith Curry <curry.judith@gmail.com> wrote:
looks good to me

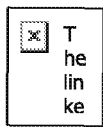
On Wed, May 14, 2025 at 10:47 AM Ross McKittrick <ross.mckitrick@gmail.com> wrote:
I made some changes to the mortality chapter. For some reason a lot of the sources in the footnotes were wrong, either the cited paper didn't say what the text discussed, the list of authors was not for that paper or the hyperlink went somewhere else. I took out the Lee and Dessler chart which is hard to read and put in the Gasparini et al chart instead.

--



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From: John Christy <climateman60@gmail.com>
Sent: Wednesday, May 14, 2025 2:17 PM
To: Judith Curry
Cc: Ross McKittrick; Roy W. Spencer; Travis Fisher; Steven Koonin
Subject: Re: Ch 12 mortality

Ross:

This first paragraph seems at odds with Chapter 7 where changes in extremes were not found. Is this a claim drawn from the IPCC docs? If so, it needs a citation.

John C.

12 Mortality from temperature extremes

12.1 Heat and cold risks

Changes in temperature extremes are among the most certain impacts expected in a warming world. Extreme heat events are likely to become more frequent while extreme cold events become less frequent. This pattern is evident in the historical period (Chapter 7) and is expected to continue with further warming.

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From: John Christy <climateman60@gmail.com>
Sent: Friday, July 11, 2025 10:28 AM
To: Judith Curry
Cc: Steven Koonin; Ross McKittrick; Roy W. Spencer; Travis Fisher; Josh Loucks
Subject: Re: change in my plans

Judy

Not a bad idea ... she has lots of federal experience and tries to keep a level head.

John C.

On Fri, Jul 11, 2025 at 9:26 AM Judith Curry <curry.judith@gmail.com> wrote:
Take a look at Betsy Weatherhead for USGCRP. In Trump I, she was appointed to lead NCA5. She would be very good IMO and I think she would do it.

On Fri, Jul 11, 2025 at 6:32 AM Steven Koonin <steven.koonin@gmail.com> wrote:

As I've just told Travis on the phone, I've decided not to pursue an IPA with DOE. Reasons include irreconcilable conflicts of interest, the constraints that would have been imposed on my activities, and the many other things on my plate –starting to reform USGCRP would not be a part-time task.

Despite this, I intend to remain fully engaged in finishing up our two documents and in post-release activities.

SEK

PS Happy to elaborate privately for anyone who's interested

--



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From: John Christy <climateman60@gmail.com>
Sent: Thursday, May 22, 2025 10:00 AM
To: Roy Spencer
Cc: judith curry; Steve Koonin; Ross McKittrick; Travis Fisher
Subject: Re: Chapter 5

Roy

I thought Gavin's big complaint was our referencing of trends to a common starting point. It's like a 100 m dash - we had everyone start at the starting line at the same time. Gavin wanted runners to start at different places so they crossed the 50m line at the same time and their differences at the end would be about half as much. Gavin was wrong in his depiction.

John C.

On Thu, May 22, 2025 at 3:36 AM Roy Spencer <roywspencer@hotmail.com> wrote:

I agree... Especially since Gavin was the ONLY author/expert government reviewer of the 2009 EF TSD with actual climate research credentials... he can't be ignored. Let me think about how to do it.

From: Judith Curry <curry.judith@gmail.com>
Sent: Wednesday, May 21, 2025 7:10 PM
To: John Christy <climateman60@gmail.com>
Cc: Roy Spencer <roywspencer@hotmail.com>; Steve Koonin <steven.koonin@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>
Subject: Re: Chapter 5

Not necessarily, but it would be useful to head this criticism off at the pass with some text.

On Wed, May 21, 2025 at 4:07 PM John Christy <climateman60@gmail.com> wrote:

Judy

We have the full spread of models in the tropical vertical trends. Are you thinking we should put that spread in the global satellite time series as well?

John C.

Sent from my iPhone

On May 21, 2025, at 5:38 PM, judith curry <curry.judith@gmail.com> wrote:

Main issue of concern is only comparing model mean (with a large spread) against observations

Sent from my iPhone

On May 21, 2025, at 3:29 PM, Roy Spencer <roywspencer@hotmail.com> wrote:

John, Kevin, and I have a paper in the works proving aligning time series so their linear trends start at the same beginning point gives the earliest evidence that time series have different trends.

His other criticisms are nonsense (the the 12 state corn belt is cherry picking... no, it is agriculturally critical to global grain markets, and refutes claims the the corn belt is in a period of collapse from GW.

But, to the extent Gavins blog posts carry weight (I've responded to them in my blog), I'd be glad to add whatever you all this is appropriate. I was under the impression we were not going to get into blog pissing contests.

-Roy

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Judith Curry <curry.judith@gmail.com>

Date: 5/21/25 5:06 PM (GMT-06:00)

To: Steve Koonin <steven.koonin@gmail.com>, John Christy <climateman60@gmail.com>, Ross McKittrick <ross.mckittrick@gmail.com>, Roy Spencer <roywspencer@hotmail.com>, Travis Fisher <travis.scott.fisher@gmail.com>

Subject: Chapter 5

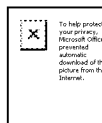
Gavin schmidt has critiqued many of the figures in this chapter

<https://www.realclimate.org/index.php/archives/2024/01/spencers-shenanigans/>

His point is well taken about only including the mean of climate model observations.

I think we should mention why this choice was made, and mention the spread, even if we don't include Gavin's critique

--



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To help protect
your privacy,
Microsoft Office
prevented
automatic
download of this
picture from the
Internet.

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From: Ross McKittrick <ross.mckittrick@gmail.com>
Sent: Wednesday, May 21, 2025 7:12 PM
To: John Christy
Cc: judith curry; Roy Spencer; Steve Koonin; Travis Fisher
Subject: Re: Chapter 5

I think our figures are fine as is. The updated M&C2020 figures include trends from all models and lead to the same conclusion as Roy's figure. There are a few outlier models with trends that match observations but in Gavin's figure by just showing uniform shading you can't tell if it's just one or a lot of models that overlap observations. With Fig 5.4 you can see how many are in the neighborhood of obs trends and how many are not.

On Wed, May 21, 2025 at 7:07 PM John Christy <climateman60@gmail.com> wrote:
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Date: 5/21/25 5:06 PM (GMT-06:00)

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Subject: Chapter 5

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From: Ross McKittrick <ross.mckittrick@gmail.com>
Sent: Sunday, May 4, 2025 10:21 AM
To: John Christy
Cc: Roy Spencer; Travis Fisher; Steven Koonin; Judith Curry
Subject: Re: Chapter 14: U.S. Vehicle-Based CO2 Emissions and the Global Climate

Thanks John. I've been detained at a conference this weekend but will be home in a few hours and I'll get this posted to the dropbox. Hope you and Sherry have a nice trip.
Ross

On Sat, May 3, 2025 at 9:47 PM John Christy <climateman60@gmail.com> wrote:
Ross

Attached is my latest work on CONUS extremes (Chapter 8). I dealt mostly with NCA5 since there won't be an NCA6 that is alarmist. I did not look at other countries since it takes years to build these kind of datasets and other countries make it hard to track down problems, let alone the data themselves.

I included something for a sidebar - PacNW 2021 heat wave which was called out by NCA5. Perhaps others might like to put a specific idea in a sidebar that goes with their chapter but is not necessarily part of the main flow.

If you want some more extreme analyses of these stations, they are quick to do. We have 31 stations in Minnesota for precipitation if you want to add an upper Midwest result. If I had time, I could build some more continuous daily datasets for precipitation, but unless I get lucky on some, they take several hours, sometimes days, per station. For several I had to manually key-in the pre-1893 data as well as other random years ... not easy for an old fart. I can assure you that no one else has datasets that are as clean as these.

I thought it appropriate to include a Canadian station (Montreal) in the Northeast given your involvement. The data were actually easy to retrieve, though they came in those dang mm.

I'll be in Hawaii Monday to Monday, but should have internet access at times. We'll be on Oahu only, so no big trips while there.

I'd like to know where Steve was driving around on our last call - couldn't tell out the car window.

Aloha.

John C.

John Christy
Director, Earth System Science Center
Professor, Atmos and Earth Science
Alabama State Climatologist
The University of Alabama in Huntsville
climateman60@gmail.com

On May 2, 2025, at 6:34 AM, Roy Spencer <roywspencer@hotmail.com> wrote:

This is quite brief, but it gets to the crux of the issue as I understand it based upon my discussions with EPA attorneys from a previous administration.

Feel free to add/subtract/edit/suggest.

-Roy

From: Roy Spencer <roywspencer@hotmail.com>

Sent: Thursday, May 1, 2025 11:49 AM

To: Ross McKittrick <ross.mckittrick@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; John Christy <climateman60@gmail.com>; Steven Koonin <steven.koonin@googlemail.com>; Judith Curry <curry.judith@gmail.com>

Subject: RE: May 1 status update

This kind of outline update is VERY helpful. I'll touch base with John and do something on U.S. vehicle emissions.

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Ross McKittrick <ross.mckittrick@gmail.com>

Date: 5/1/25 11:31 AM (GMT-06:00)

To: Travis Fisher <travis.scott.fisher@gmail.com>, "Roy W. Spencer" <roywspencer@hotmail.com>, John Christy <climateman60@gmail.com>, Steven Koonin <steven.koonin@googlemail.com>, Judith Curry <curry.judith@gmail.com>

Subject: May 1 status update

Here's the current Table of Contents as I have it and the status of each chapter

Secretary's Preface - **needed**

Introduction: Overview and purpose of document - **draft posted**

Part I: Direct human influence on ecosystems and the climate

1 Carbon dioxide as distinct from criteria air contaminants **draft posted**

2 Global greening and CO2 fertilization **draft posted**

3 Increasing CO2 and the alkaline oceans **draft posted**

4 Anthropogenic Radiative forcing

4.1 Components of anthropogenic radiative forcing and their history to date **draft posted**

4.2 The carbon cycle and future emission scenarios **draft posted**

4.3 Aerosols and the uncertainties associated with them **draft posted**

Part II: Climate response to greenhouse gas emissions

5 Measuring climate sensitivity to CO2 doubling **draft posted**

6 Models versus observations in recent past **draft posted**

7 Uncertainties in analysis of attribution **draft not posted**

8 Evidence on trends and attributable changes in extreme weather **draft posted**

9 Sea level rise **draft not posted**

Part III: Impacts on ecosystems and society
10 Climate change and US agriculture **draft posted**
11 Managing risks of extreme weather **draft not posted**
12 Mortality risk from extreme heat and cold **draft not posted**
13 Climate change and the Economy
13.1 Climate change and economic growth **draft posted**
13.2 The Social Cost of Carbon **draft posted**
14 US vehicle-based CO2 emissions and the global climate **draft not posted**

Chapters without drafts posted:

Ch 7 - Judy I think you're working on that one?

Ch 9 - Judy do you have this draft? I lost track of who's working on this.

Ch11 - Should Ch 11 and 12 be merged?

- Judy has written an overview on the topic of managing risks and I have some material to add from the econ literature.
- John can you write a section about the hot/cold extremes data that you've tabulated and charted? It provides a very clear picture that the US climate is getting less extreme and the warming is mainly in the form of fewer cold events not more heat waves.
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Ch 14 - Roy did you have something written on US vehicle emissions? I guess we're just working out the fractional contribution.

Also the document would benefit from a glossary of technical terms, acronyms etc. Roy could you make a start on that?

Cheers,
Ross

<U.S. Vehicle-Based CO2 Emissions and the Global Climate [RS].docx>

From: Judith Curry [curry.judith@gmail.com]
Sent: 5/4/2025 3:09:39 PM
To: John Christy [climateman60@gmail.com]
CC: Roy Spencer [roywspencer@hotmail.com]; Ross McKittrick [ross.mckittrick@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]; Steven Koonin [steven.koonin@gmail.com]
Subject: Re: Chapter 14: U.S. Vehicle-Based CO2 Emissions and the Global Climate
Attachments: [8]_Extremes_T_P_3May[JRC] JAC.docx

Hi John, I really like this chapter, comments are attached (mostly editorial)

On Sat, May 3, 2025 at 6:47 PM John Christy <climateman60@gmail.com> wrote:
Ross

Attached is my latest work on CONUS extremes (Chapter 8). I dealt mostly with NCA5 since there won't be an NCA6 that is alarmist. I did not look at other countries since it takes years to build these kind of datasets and other countries make it hard to track down problems, let alone the data themselves.

I included something for a sidebar - PacNW 2021 heat wave which was called out by NCA5. Perhaps others might like to put a specific idea in a sidebar that goes with their chapter but is not necessarily part of the main flow.

If you want some more extreme analyses of these stations, they are quick to do. We have 31 stations in Minnesota for precipitation if you want to add an upper Midwest result. If I had time, I could build some more continuous daily datasets for precipitation, but unless I get lucky on some, they take several hours, sometimes days, per station. For several I had to manually key-in the pre-1893 data as well as other random years ... not easy for an old fart. I can assure you that no one else has datasets that are as clean as these.

I thought it appropriate to include a Canadian station (Montreal) in the Northeast given your involvement. The data were actually easy to retrieve, though they came in those dang mm.

I'll be in Hawaii Monday to Monday, but should have internet access at times. We'll be on Oahu only, so no big trips while there.

I'd like to know where Steve was driving around on our last call - couldn't tell out the car window.

Aloha.

John C.

John Christy
Director, Earth System Science Center
Professor, Atmos and Earth Science
Alabama State Climatologist
The University of Alabama in Huntsville
climateman60@gmail.com

On May 2, 2025, at 6:34 AM, Roy Spencer <roywspencer@hotmail.com> wrote:

This is quite brief, but it gets to the crux of the issue as I understand it based upon my discussions with EPA attorneys from a previous administration.

Feel free to add/subtract/edit/suggest.

-Roy

From: Roy Spencer <roywspencer@hotmail.com>

Sent: Thursday, May 1, 2025 11:49 AM

To: Ross McKittrick <ross.mckittrick@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; John Christy <climateman60@gmail.com>; Steven Koonin <steven.koonin@googlemail.com>; Judith Curry <curry.judith@gmail.com>

Subject: RE: May 1 status update

This kind of outline update is VERY helpful. I'll touch base with John and do something on U.S. vehicle emissions.

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Ross McKittrick <ross.mckittrick@gmail.com>

Date: 5/1/25 11:31 AM (GMT-06:00)

To: Travis Fisher <travis.scott.fisher@gmail.com>, "Roy W. Spencer" <roywspencer@hotmail.com>, John Christy <climateman60@gmail.com>, Steven Koonin <steven.koonin@googlemail.com>, Judith Curry <curry.judith@gmail.com>

Subject: May 1 status update

Here's the current Table of Contents as I have it and the status of each chapter

Secretary's Preface - **needed**

Introduction: Overview and purpose of document - **draft posted**

Part I: Direct human influence on ecosystems and the climate

1 Carbon dioxide as distinct from criteria air contaminants **draft posted**

2 Global greening and CO2 fertilization **draft posted**

3 Increasing CO2 and the alkaline oceans **draft posted**

4 Anthropogenic Radiative forcing

4.1 Components of anthropogenic radiative forcing and their history to date **draft posted**

4.2 The carbon cycle and future emission scenarios **draft posted**

4.3 Aerosols and the uncertainties associated with them **draft posted**

Part II: Climate response to greenhouse gas emissions

5 Measuring climate sensitivity to CO2 doubling **draft posted**

6 Models versus observations in recent past **draft posted**

7 Uncertainties in analysis of attribution **draft not posted**

8 Evidence on trends and attributable changes in extreme weather **draft posted**

9 Sea level rise **draft not posted**

Part III: Impacts on ecosystems and society

10 Climate change and US agriculture **draft posted**

11 Managing risks of extreme weather **draft not posted**

12 Mortality risk from extreme heat and cold **draft not posted**

13 Climate change and the Economy

13.1 Climate change and economic growth **draft posted**

13.2 The Social Cost of Carbon **draft posted**

14 US vehicle-based CO2 emissions and the global climate **draft not posted**

Chapters without drafts posted:

Ch 7 - Judy I think you're working on that one?

Ch 9 - Judy do you have this draft? I lost track of who's working on this.

Ch11 - Should Ch 11 and 12 be merged?

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Network
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<http://www.cfanclimate.net>

Chapter 8

~~Thoughts on Changes in short-term extreme temperature and precipitation events~~

Extremes in temperature and precipitation are generally events of short duration that often disrupt infrastructure and therefore human health and thriveability. Indeed, the ability of any surface-dwelling species to live productively is somewhat constrained by these near-surface air temperature or precipitation extremes which in essence create the bounding limits for survival. The issue here is whether these extremes, and their attendant potential danger, may be changing in response to increases in infrared-absorbing greenhouse gases (*GHGs*) (e.g., IPCC AR6 Seneviratne et al. 2021).

Unfortunately, the sample of time from which we are able to quantitatively analyze the variations of extreme events is quite brief, around 130 years. This period certainly does not begin to contain all of the extreme events that the climate system, ~~driven by the interaction of two turbulent and chaotic fluids (the atmosphere and ocean),~~ is able to generate. ~~One should appreciate that~~ Over geologic time the climate system has generated an (essentially) infinite variety of patterns and extremes which we humans have never observed, and thus which do not enter our databases from which extreme statistics are determined [see 6.4]. Thus, assuming that a new climate pattern or event in our lifetime is somehow the result of enhanced GHG concentrations requires ~~one to restrict the climate system's wide capabilities in order to conclude~~ the assumption that natural variations are insignificant. This is especially true for precipitation events. With this caveat in mind we ~~will~~ examine the evidence for changes in weather and climate extremes.

Extremes in daily temperatures in the Conterminous US (CONUS)

~~Available to us are~~ Daily maximum temperatures in the warm season (TMax, May-Sep) and daily minimum temperatures in the cold season (TMin, Dec-Mar) are available, beginning in Dec 1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (Quinlan et al. 1987, Karl et al. 1990). These